# Dark Energy and Cosmic Sound

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(Steward Observatory)

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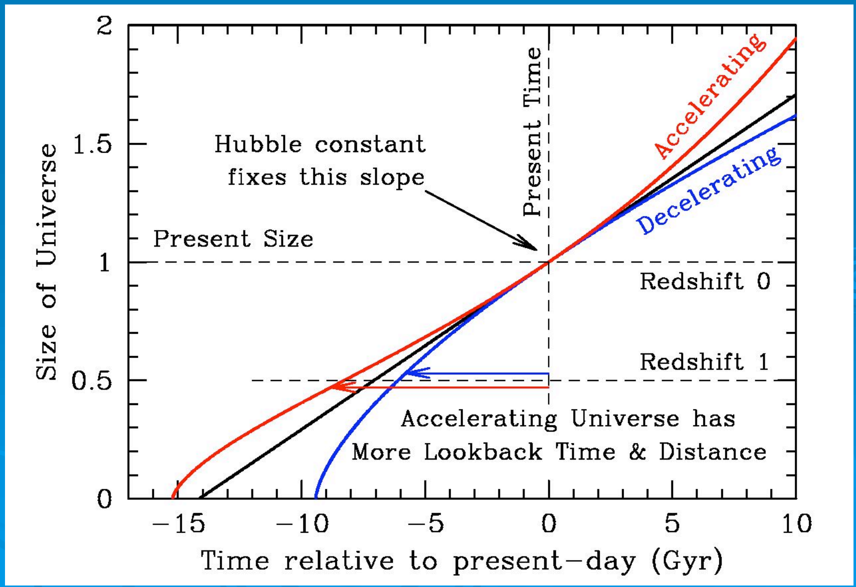
# Dark Energy is Mysterious

- Observations suggest that the expansion of the universe is presently accelerating.
  - Normal matter doesn't do this!
  - Requires exotic new physics.
    - Cosmological constant?
    - Very low mass field?
    - Some alteration to gravity?
- We have no compelling theory for this!
  - Need observational measure of the time evolution of the effect.

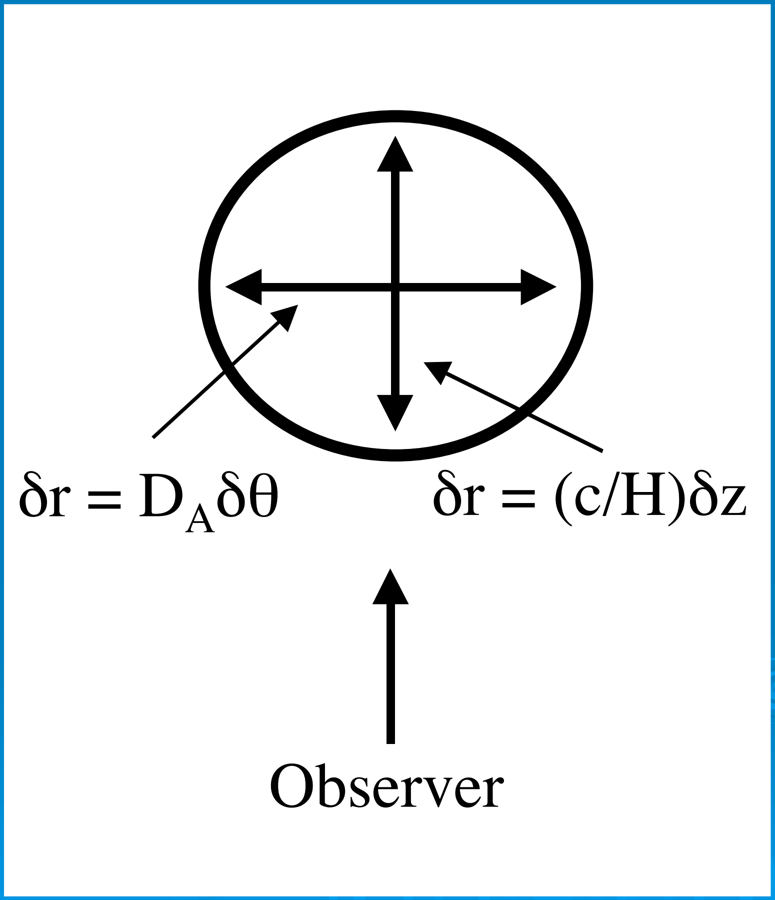


# A Quick Distance Primer

- The homogeneous metric is described by two quantities:
  - The size as a function of time, $a(t)$. Equivalent to the Hubble parameter $H(z) = d \ln(a)/dt$.
  - The spatial curvature, parameterized by $\Omega_k$.
- The distance is then

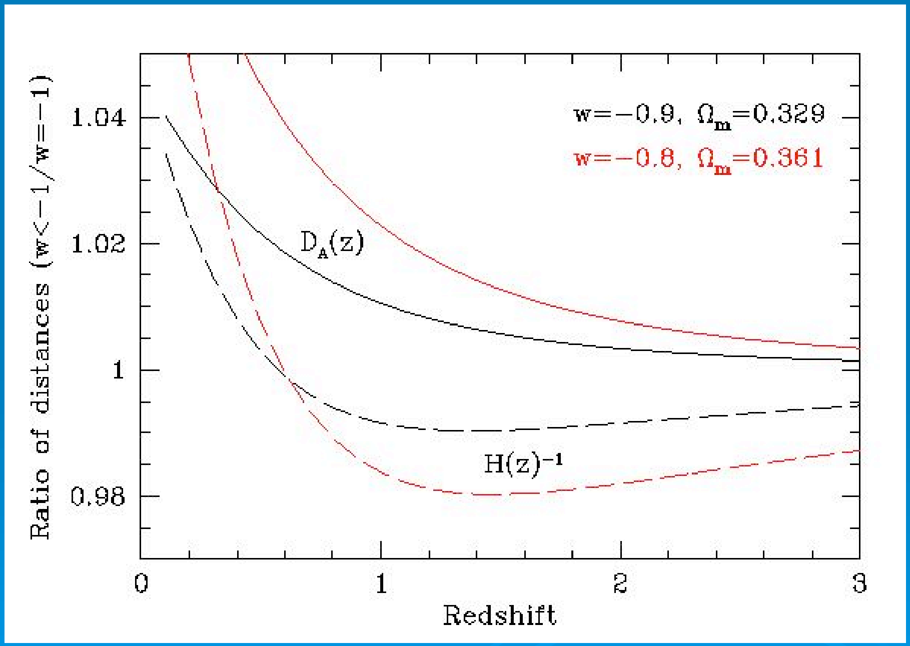
$$D = \int_0^z \frac{c\,dz}{H(z)} \quad \text{(flat)}$$

- $H(z)$ depends on the dark energy density.



# Dark Energy is Subtle

- Parameterize by equation of state, $w = p/\rho$, which controls how the energy density evolves with time.
- Measuring $w(z)$ requires exquisite precision.



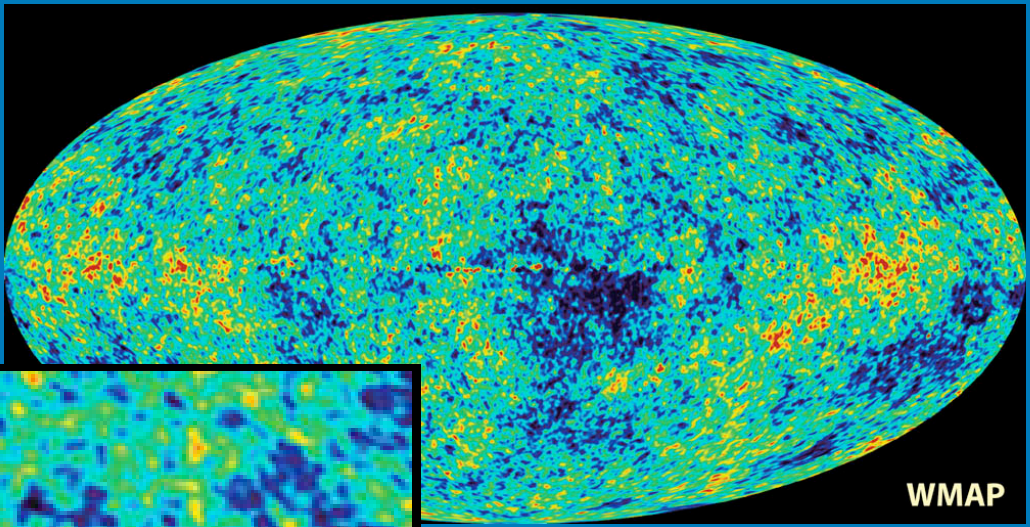

Comparing Cosmologies

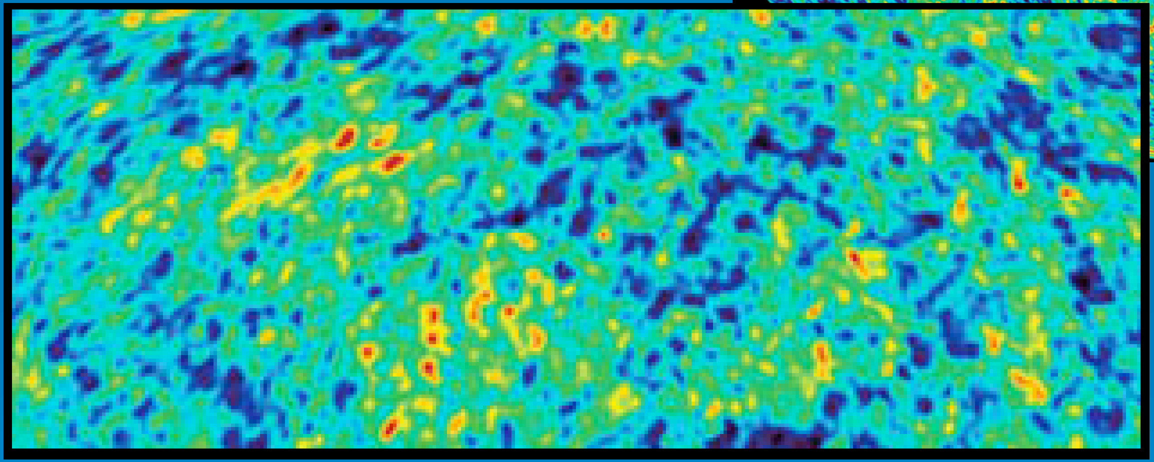
- Varying $w$ assuming perfect CMB:
  - Fixed $\Omega_m h^2$
  - $D_A(z=1000)$
- $dw/dz$ is even harder.
- Need precise, redundant observational probes!

# Outline

- Baryon acoustic oscillations as a standard ruler.
- Detection of the acoustic signature in the SDSS Luminous Red Galaxy sample at $z$=0.35.
  - Cosmological constraints therefrom.
- Large galaxy surveys at higher redshifts.
  - Future surveys could measure $H(z)$ and $D_A(z)$ to few percent from $z$=0.3 to $z$=3.
  - Assess the leverage on dark energy and compare to alternatives.

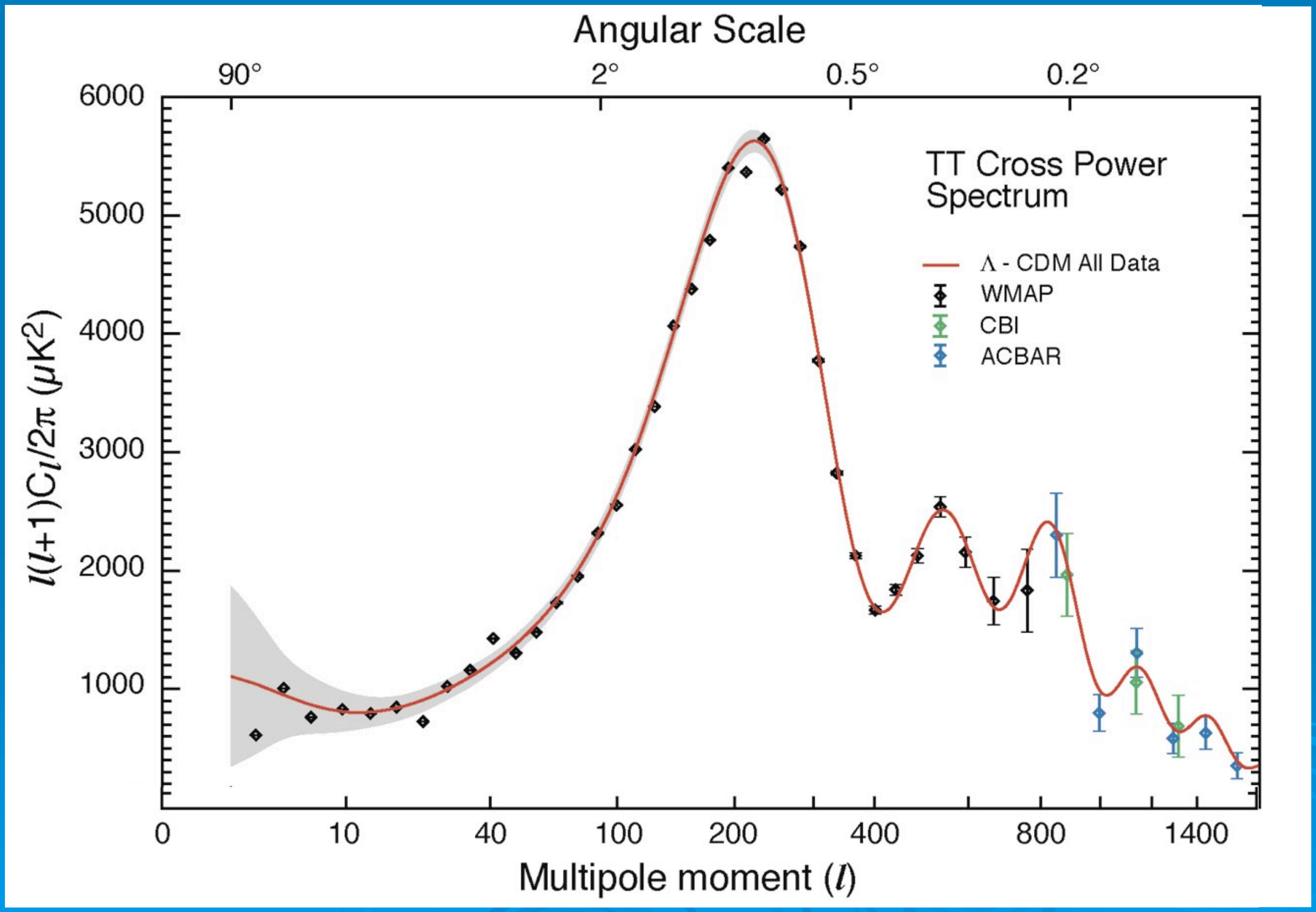
# Acoustic Oscillations in the CMB



- Although there are fluctuations on all scales, there is a characteristic angular scale.

# Acoustic Oscillations in the CMB




WMAP team (Bennett et al. 2003)

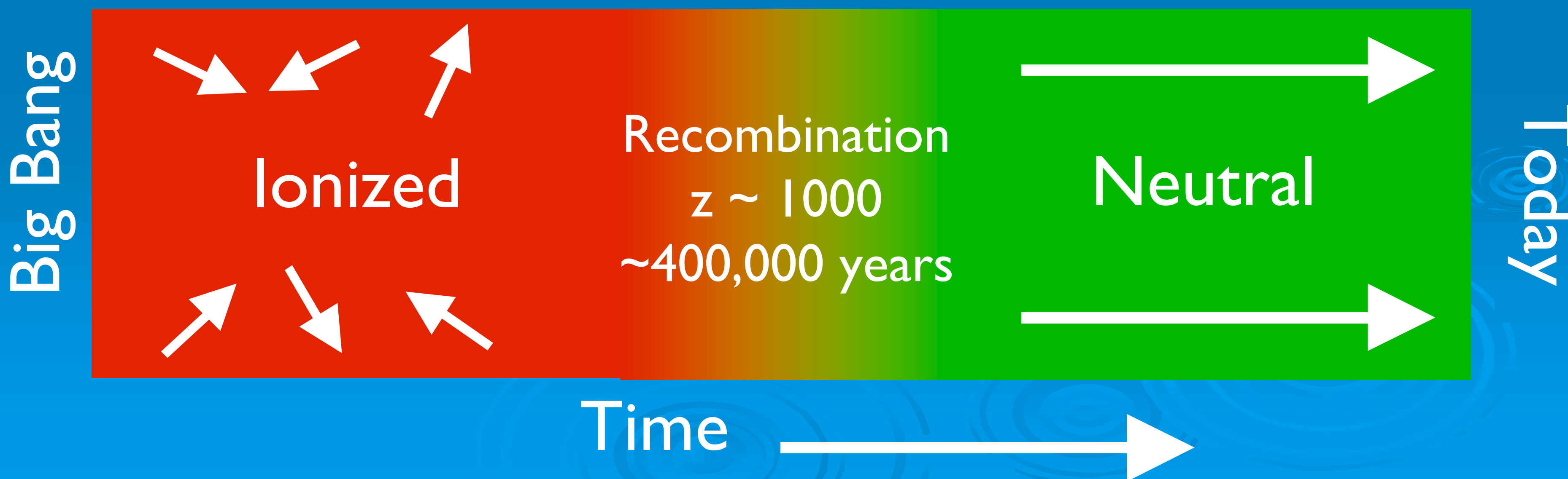
# Sound Waves in the Early Universe

**Before recombination:**

- Universe is ionized.
- Photons provide enormous pressure and restoring force.
- Perturbations oscillate as acoustic waves.

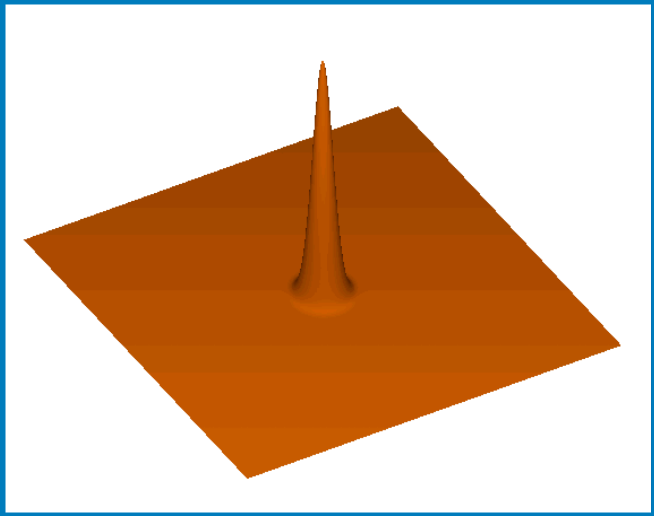
**After recombination:**

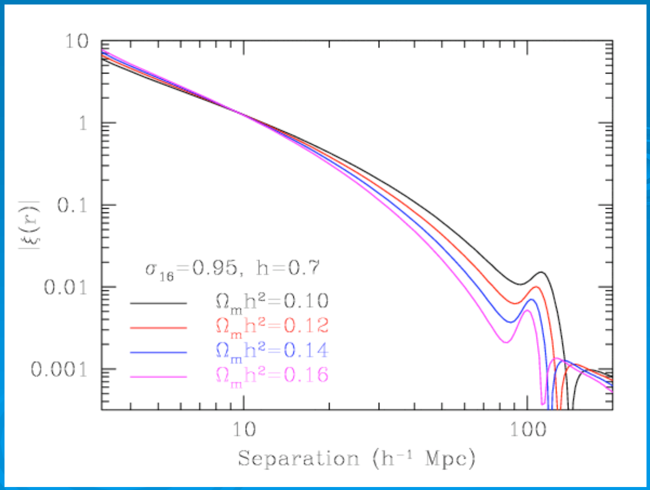
- Universe is neutral.
- Photons can travel freely past the baryons.
- Phase of oscillation at $t_{rec}$ affects late-time amplitude.



# Sound Waves

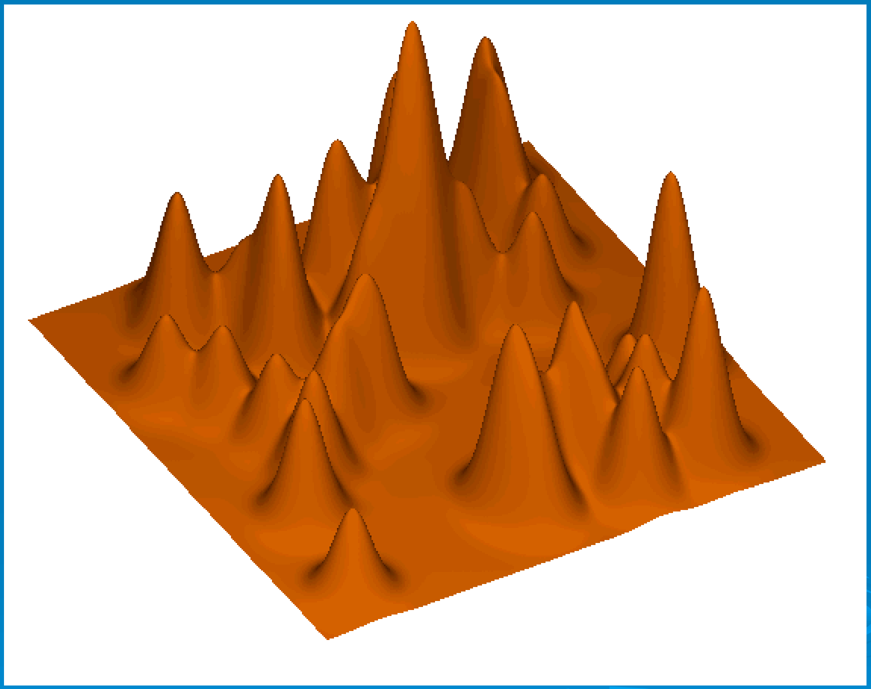
- Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.
- Sound speed plummets. Wave stalls at a radius of 150 Mpc.
- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies. Preferred separation of 150 Mpc.



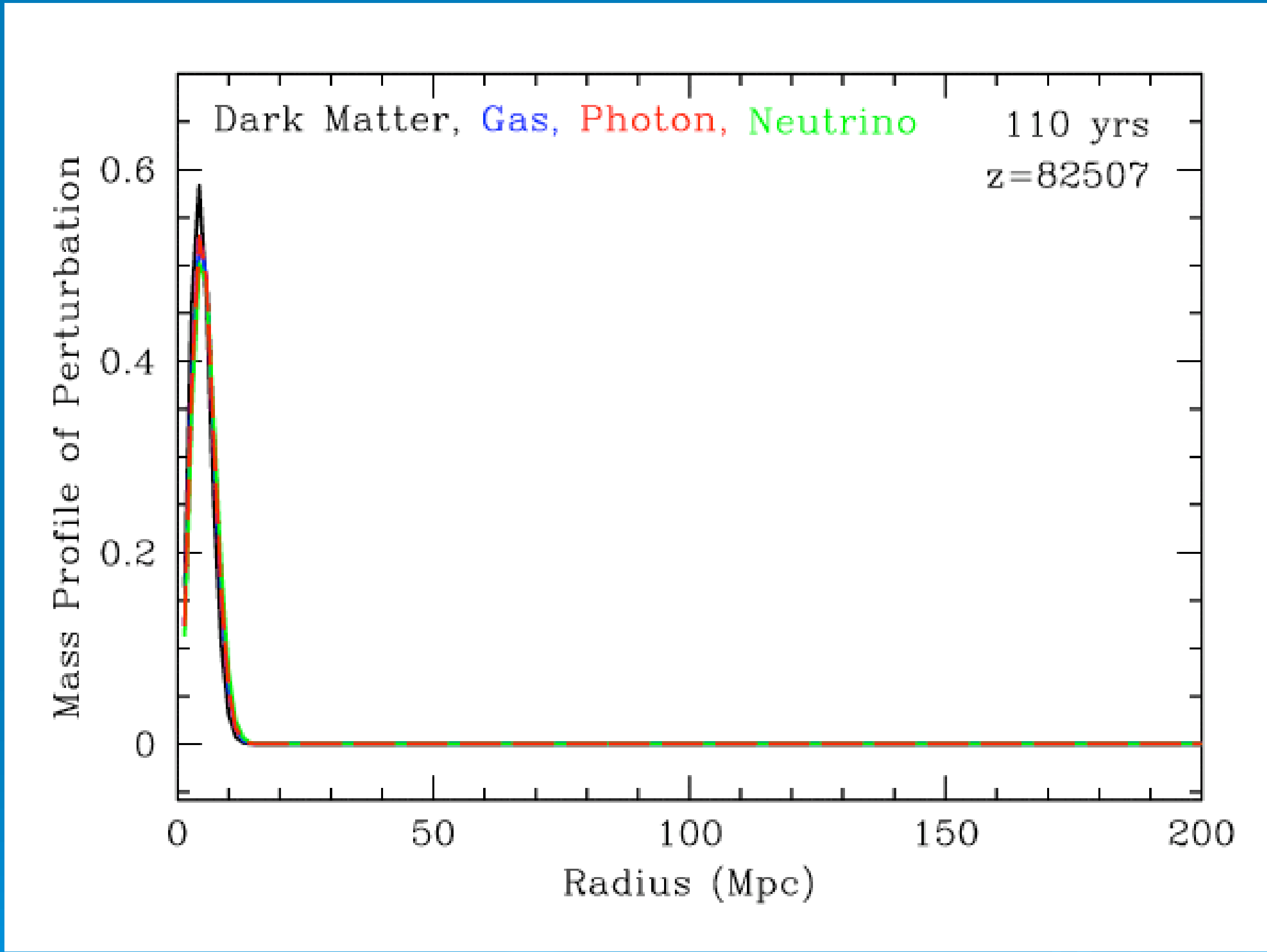


# A Statistical Signal

- The Universe is a super-position of these shells.
- The shell is weaker than displayed.
- Hence, you do not expect to see bullseyes in the galaxy distribution.
- Instead, we get a 1% bump in the correlation function.



# Response of a point perturbation

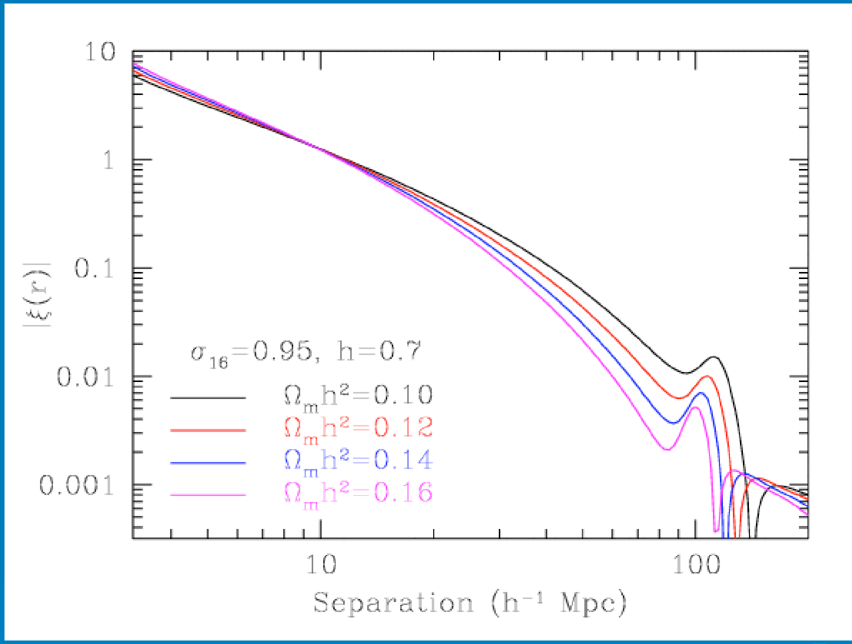



Remember: This is a tiny ripple on a big background.

Based on CMBfast outputs (Seljak & Zaldarriaga). Green's function view from Bashinsky & Bertschinger 2001.

# Theory and Observables

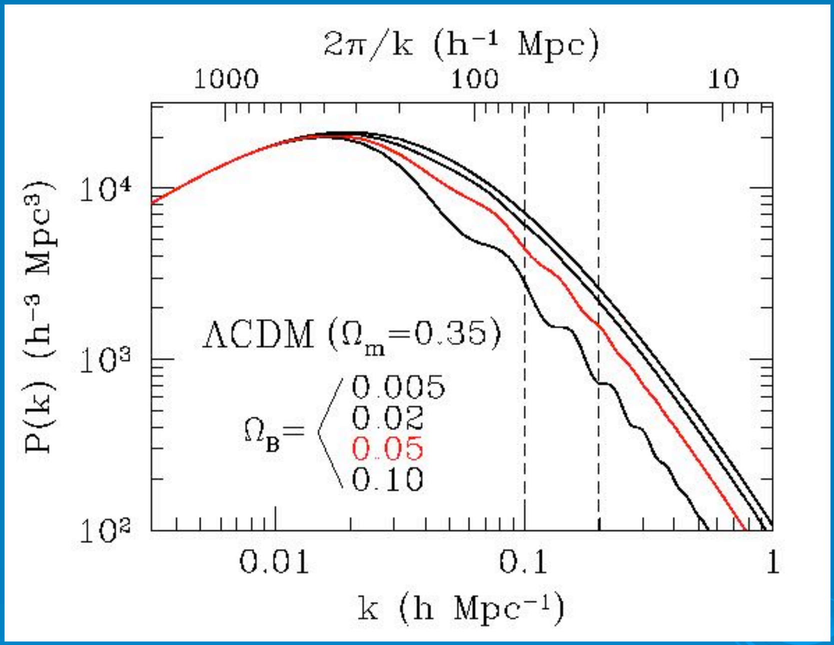
- Linear clustering is specified in proper distance by $\Omega_m h^2$, $\Omega_b h^2$, and $n$.
- Two scales: acoustic scale and M-R equality horizon scale.
- Measuring both breaks degeneracy between $\Omega_m h^2$ and distance to $z$=0.35.




$\Omega_m h^2$ shifts ratio of large to small-scale clustering, but doesn't move the acoustic scale much.

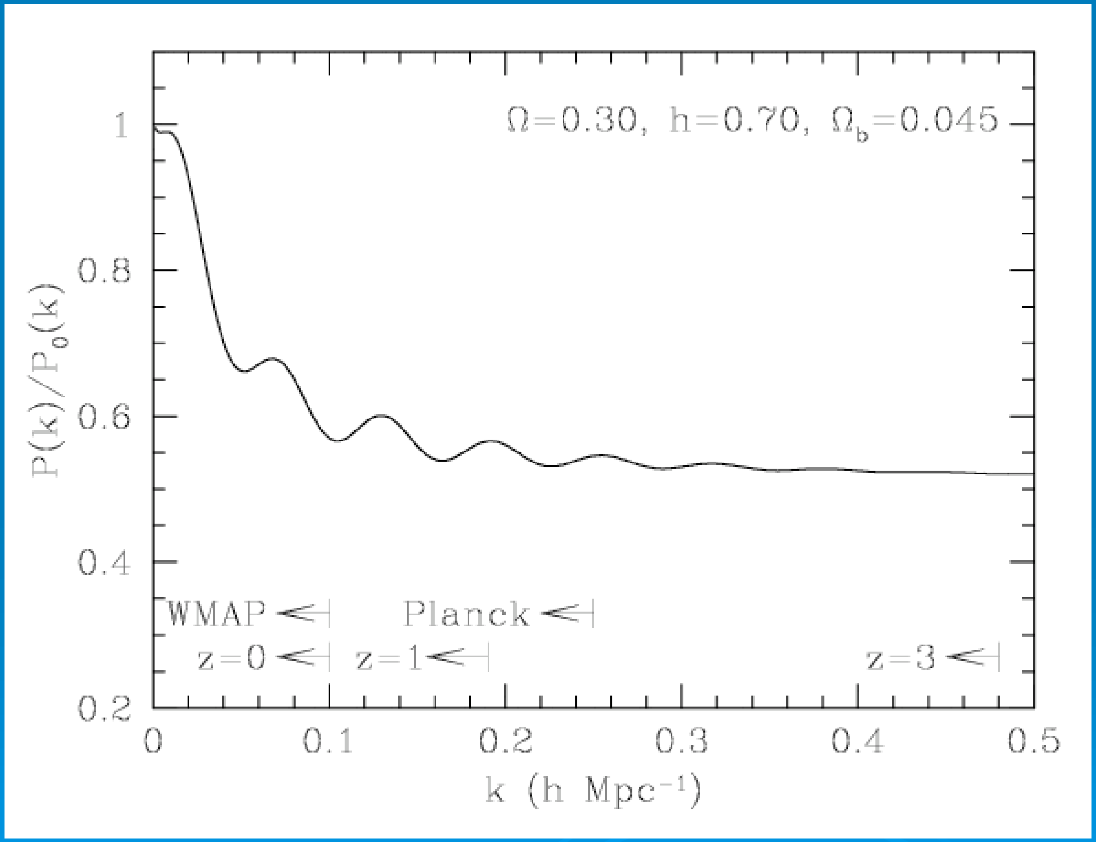
# Acoustic Oscillations in Fourier Space

- A crest launches a planar sound wave, which at recombination may or may not be in phase with the next crest.
- Get a sequence of constructive and destructive interferences as a function of wavenumber.
- Peaks are weak — suppressed by the baryon fraction.
- Higher harmonics suffer from Silk damping.




Linear regime matter power spectrum

# Acoustic Oscillations, Reprise

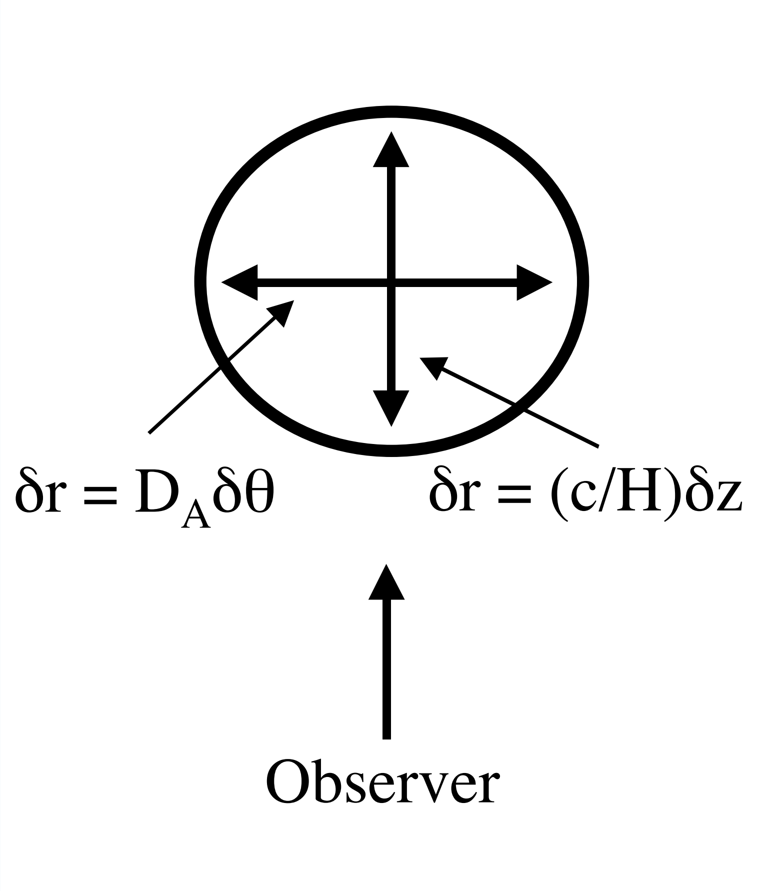



Linear regime matter power spectrum

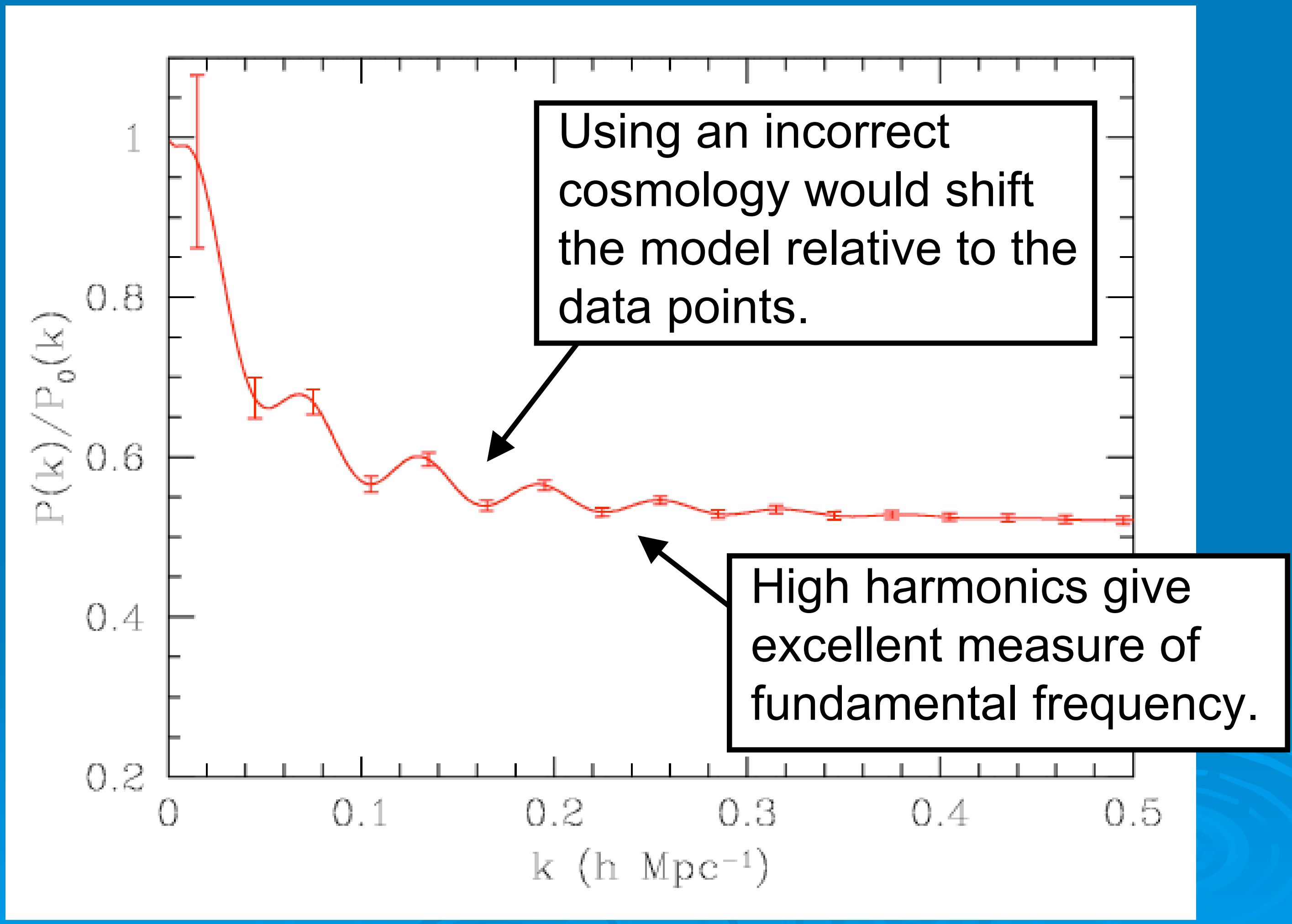
- Divide by zero-baryon reference model.
- Acoustic peaks are 10% modulations.
- Requires large surveys to detect!

# A Standard Ruler

- The acoustic oscillation scale depends on the sound speed and the propagation time.
  - These depend on the matter-to-radiation ratio ($\Omega_m h^2$) and the baryon-to-photon ratio ($\Omega_b h^2$).
- The CMB anisotropies measure these and fix the oscillation scale.
- In a redshift survey, we can measure this along and across the line of sight.
- Yields $H(z)$ and $D_A(z)$!

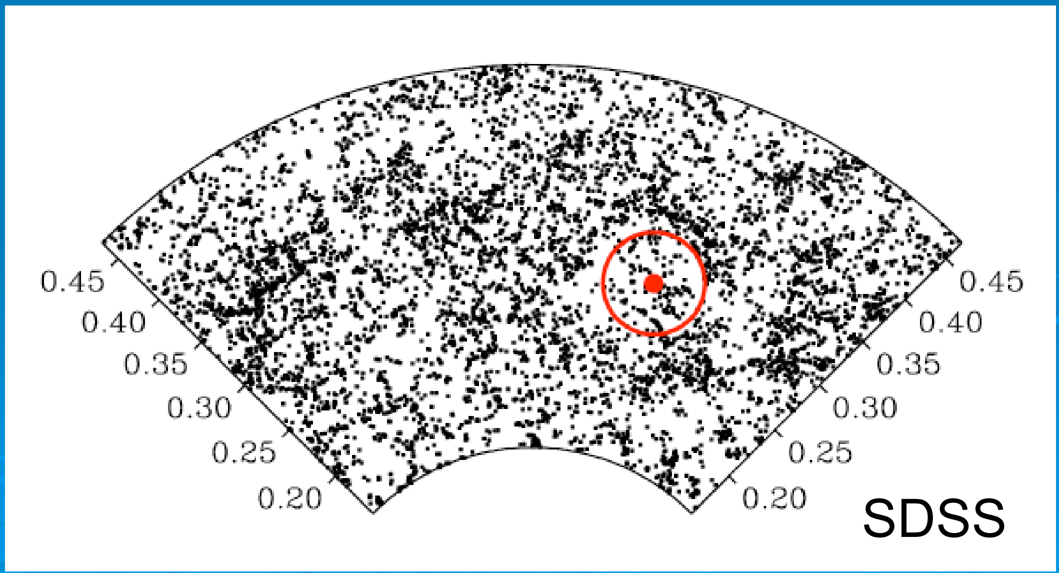


# Measuring the Acoustic Scale



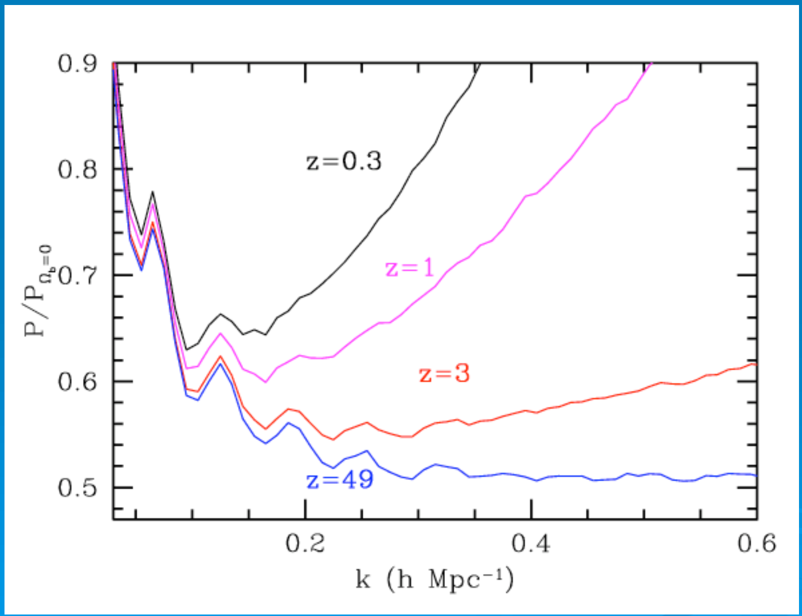
# Galaxy Redshift Surveys

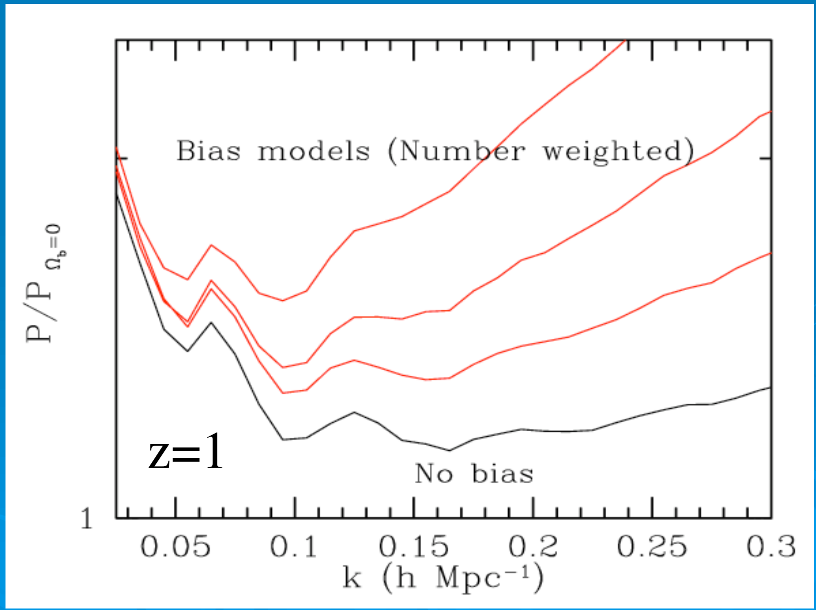
- Redshift surveys are a popular way to measure the 3-dimensional clustering of matter.
- But there are complications from:
  - Non-linear structure formation
  - Bias (light ≠ mass)
  - Redshift distortions
- Do these affect the acoustic signatures?



# Nonlinearities & Bias

- Non-linear gravitational collapse erases acoustic oscillations on small scales. However, large scale features are preserved.
- Clustering bias and redshift distortions alter the power spectrum, but they don't create preferred scales at 100$h^{-1}$ Mpc!
- Acoustic peaks expected to survive in the linear regime.

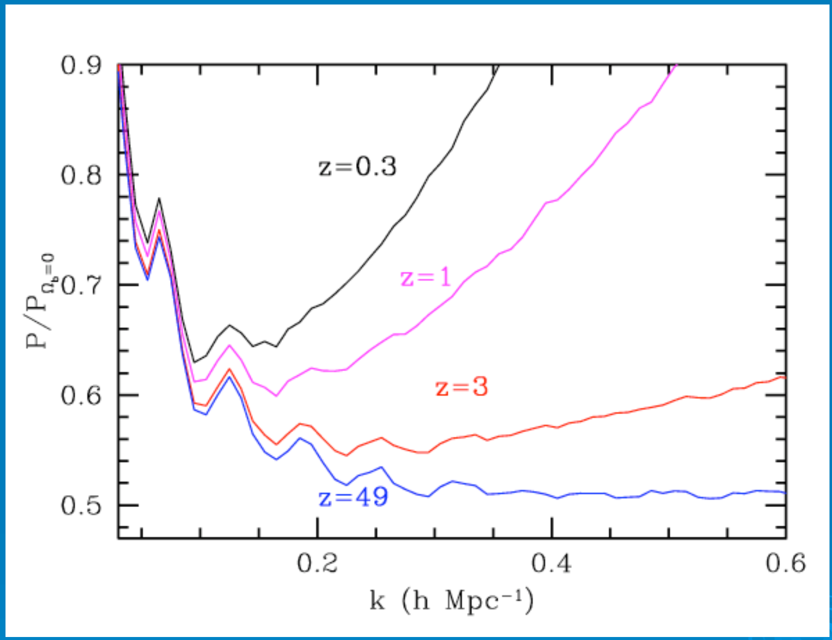



Meiksen & White (1997), Seo & DJE (2005)

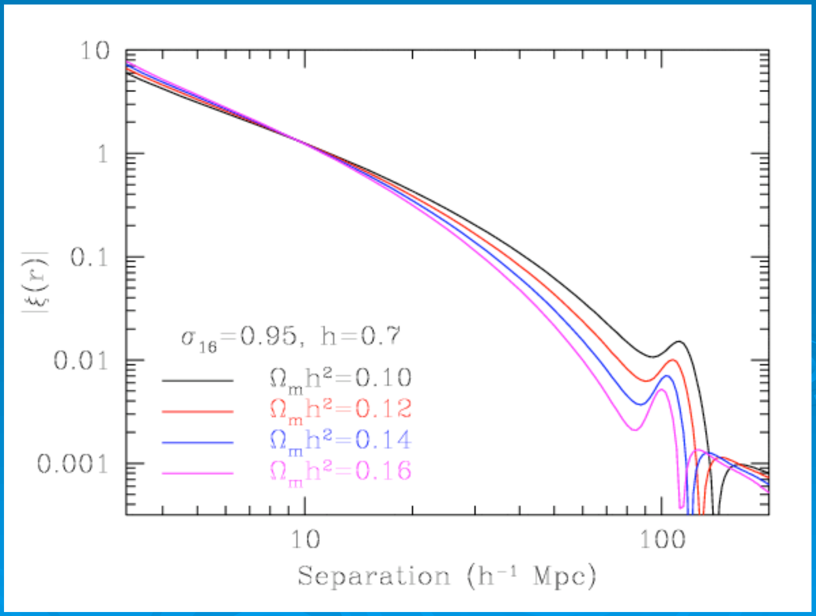
# Nonlinearities in P(k)

- How does nonlinear power enter?
  - Shifting P(k)?
  - Erasing high harmonics?
  - Shifting the scale?
- Acoustic peaks are more robust than one might have thought.
- Beat frequency difference between peaks and troughs of higher harmonics still refers to very large scale.



# Nonlinearities in $\xi(r)$

- The acoustic signature is carried by pairs of galaxies separated by 150 Mpc.
- Nonlinearities push galaxies around by 3-10 Mpc. Broadens peak, erasing higher harmonics.
- Moving the scale requires net infall on 100 $h^{-1}$ Mpc scales.
  - This depends on the over-density inside the sphere, which is about $J_3(r)/r^3 \sim 1\%$.
  - Over- and underdensities cancel, so mean shift is $O(10^{-4})$.
- Simulations show no evidence for any bias at 1% level.

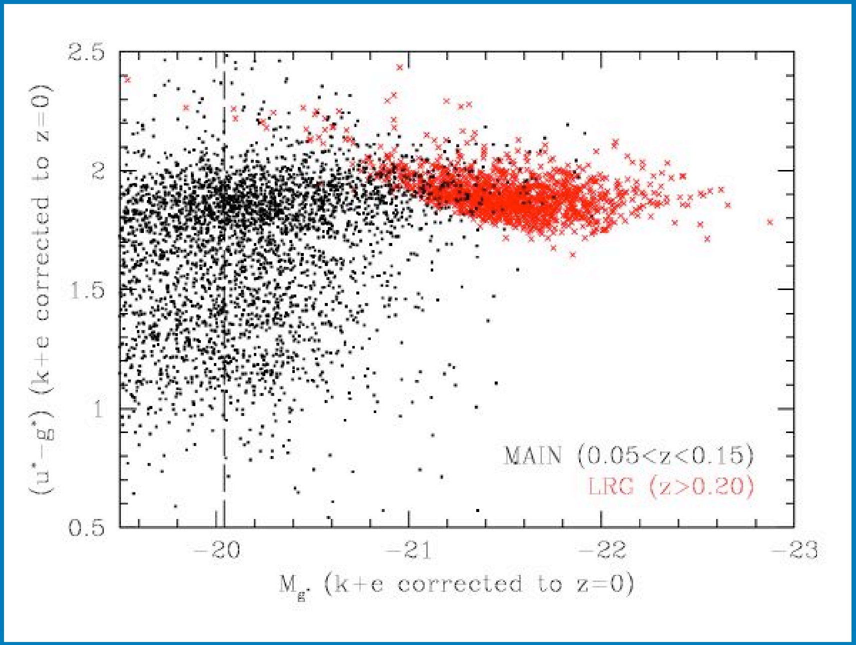


# Virtues of the Acoustic Peaks

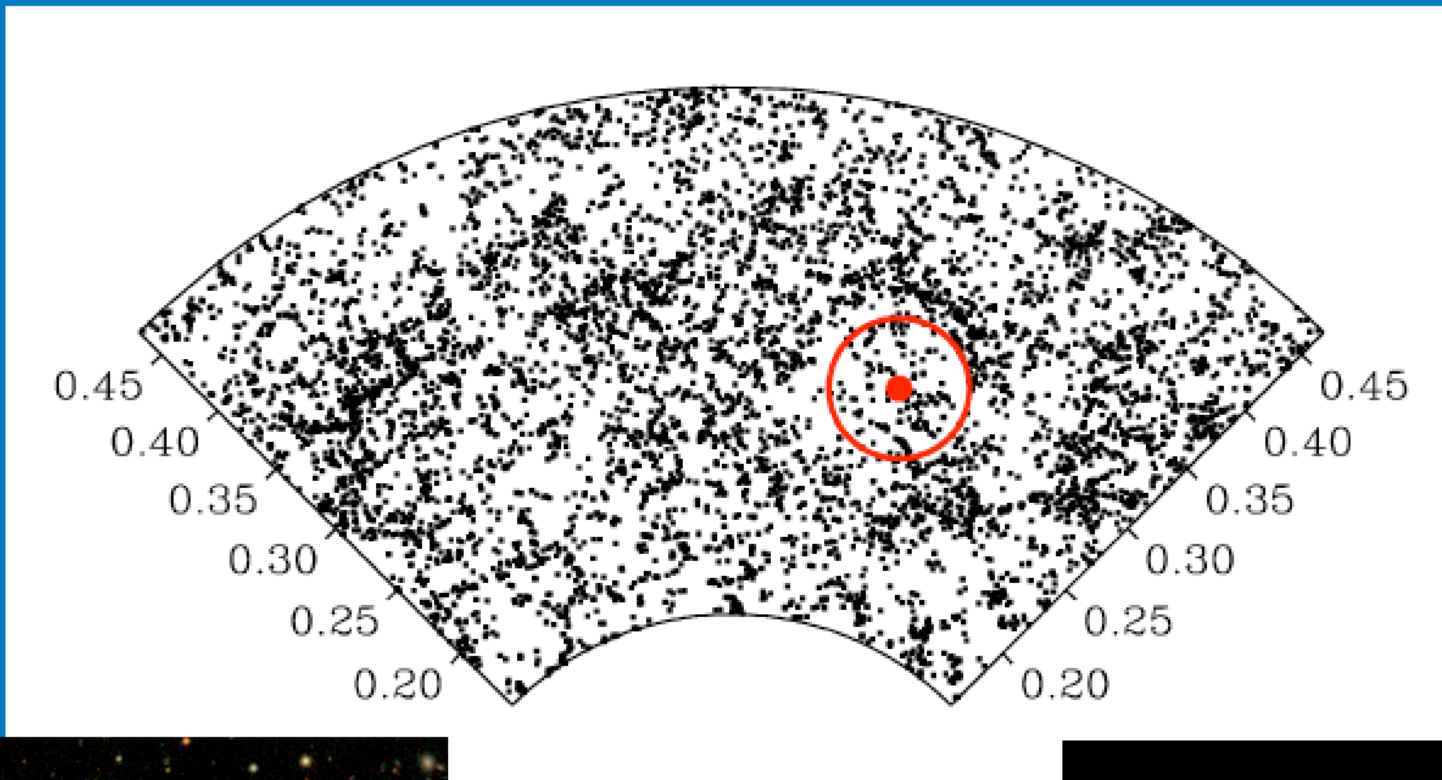
- Measuring the acoustic peaks across redshift gives a purely geometrical measurement of cosmological distance.
- The acoustic peaks are a manifestation of a preferred scale.
  - Non-linearity, bias, redshift distortions shouldn't produce such preferred scales, certainly not at 100 Mpc.
  - Method should be robust.
- However, the peaks are weak in amplitude and are only available on large scales (30 Mpc and up). Require huge survey volumes.

# Introduction to SDSS LRGs

- SDSS uses color to target luminous, early-type galaxies at $0.2<z<0.5$.
  - Fainter than MAIN ($r<19.5$)
  - About 15/sq deg
  - Excellent redshift success rate
- The sample is close to mass-limited at $z<0.38$. Number density ~ $10^{-4}$ $h^3$ Mpc$^{-3}$.




- Science Goals:
  - Clustering on largest scales
  - Galaxy clusters to z~0.5
  - Evolution of massive galaxies


0.45
0.40
0.35
0.30
0.25
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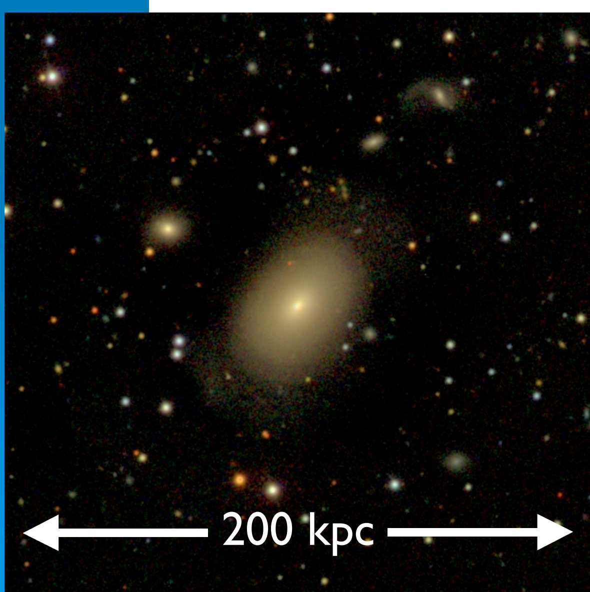
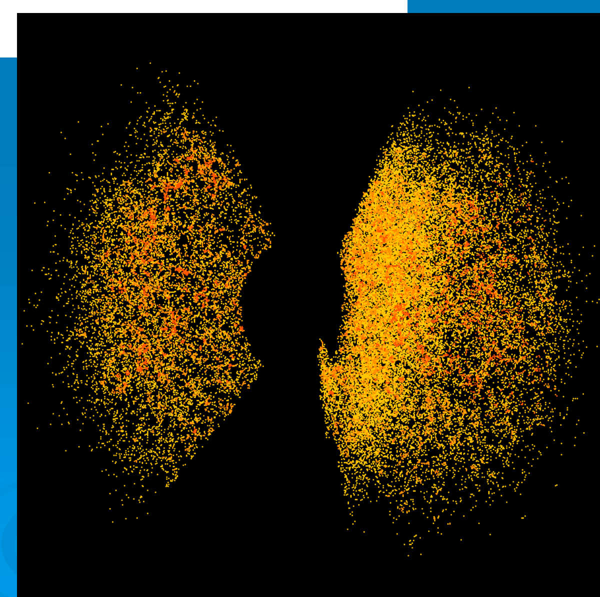
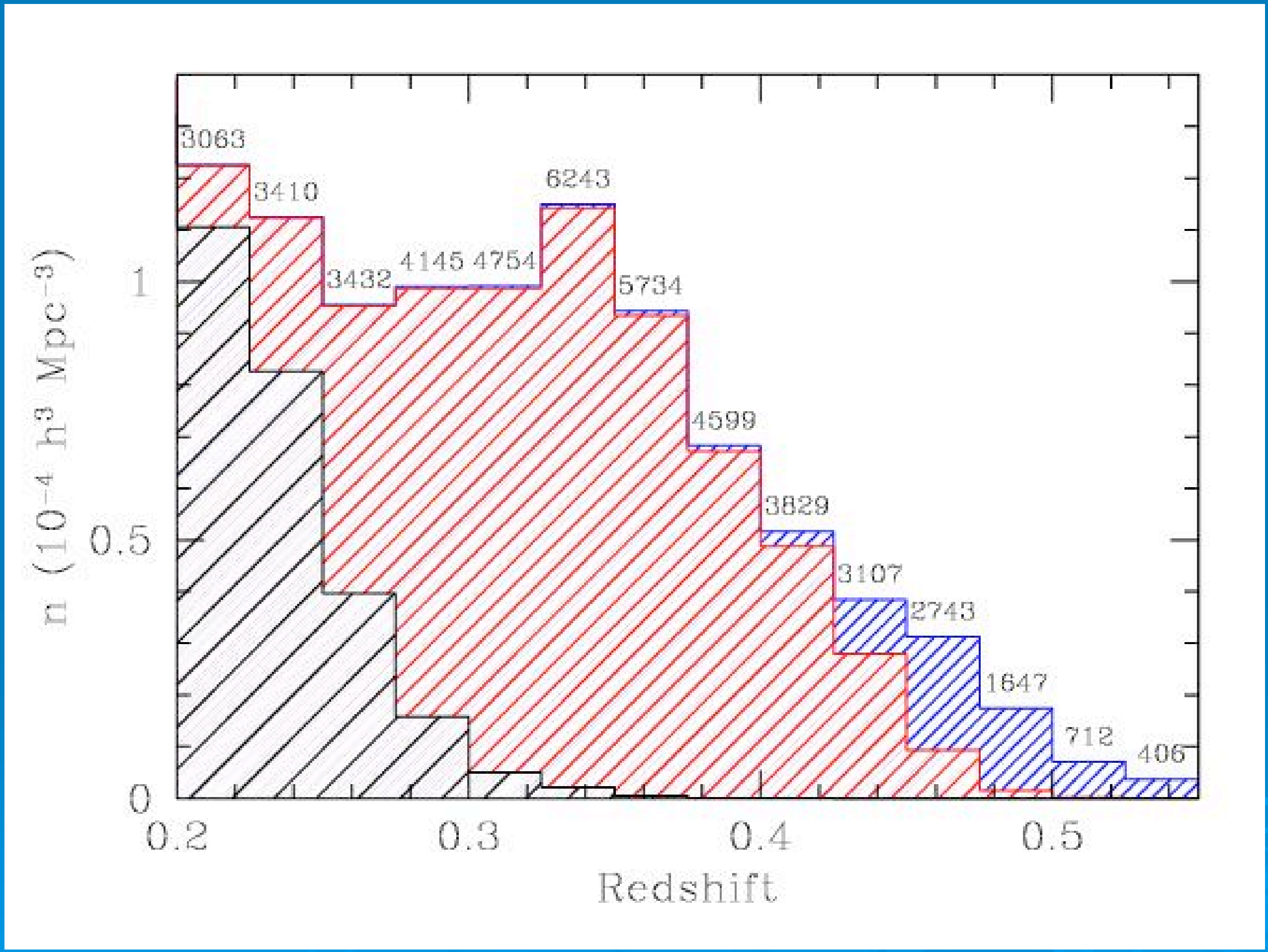
0.45
0.40
0.35
0.30
0.25
0.20

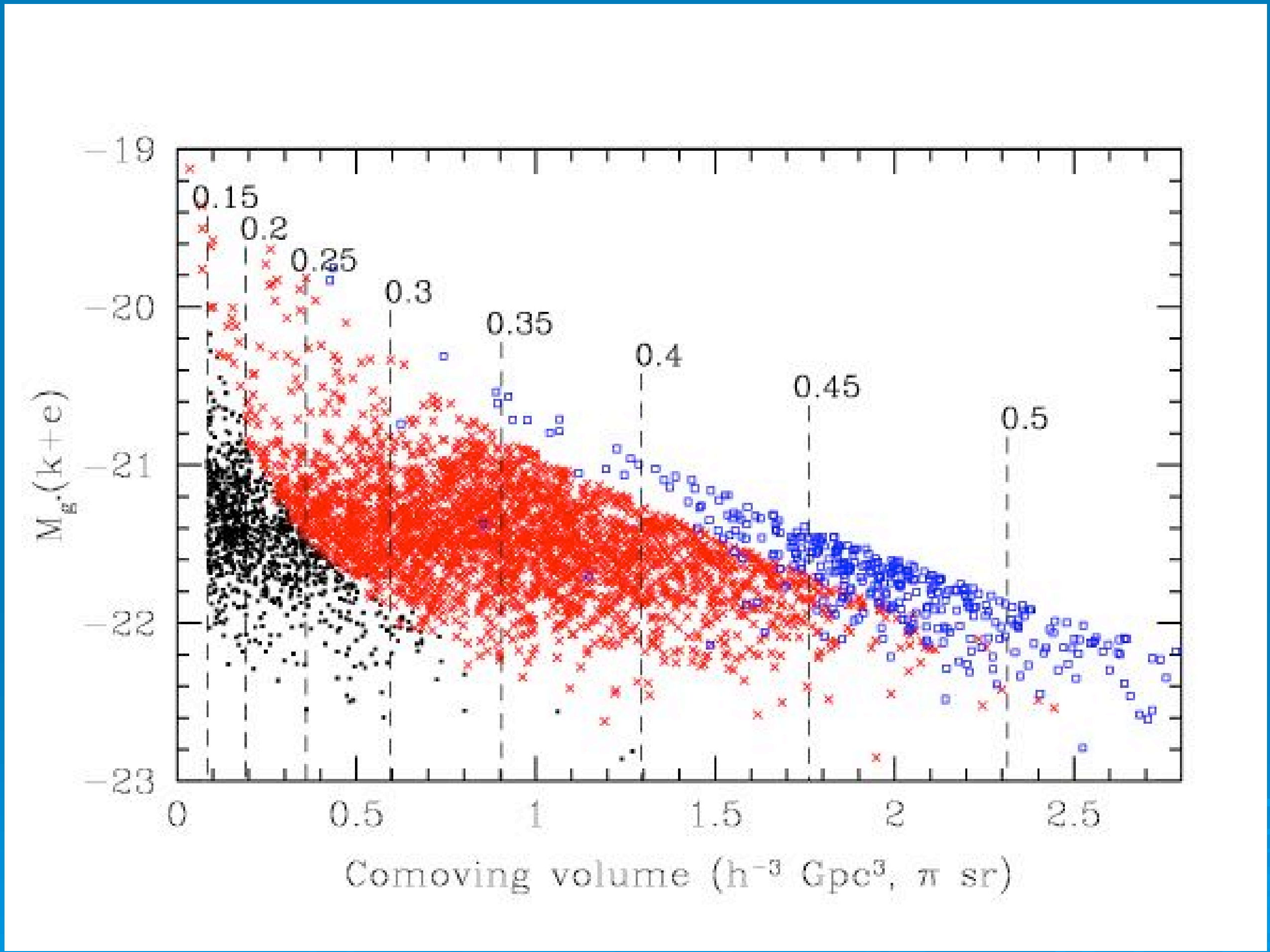

200 kpc



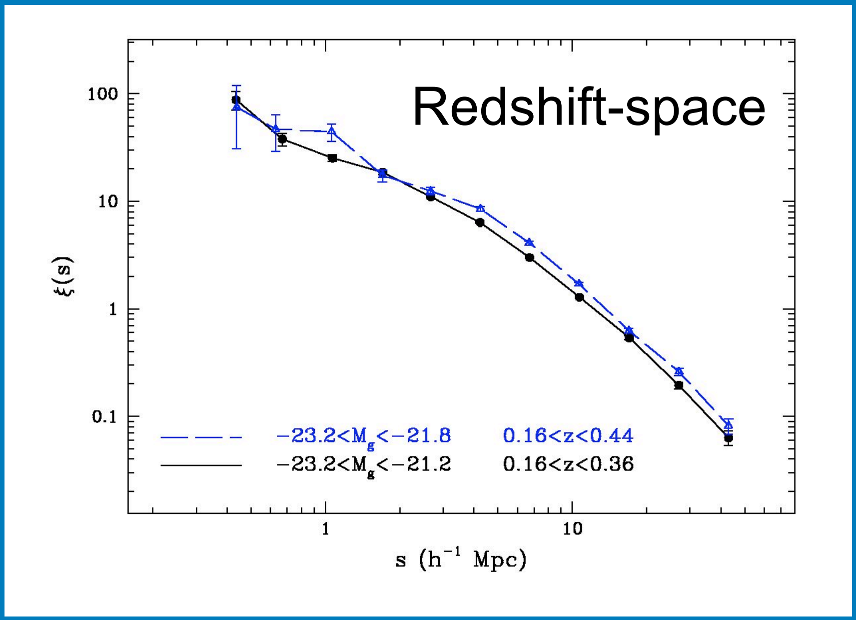
# 55,000 Spectra

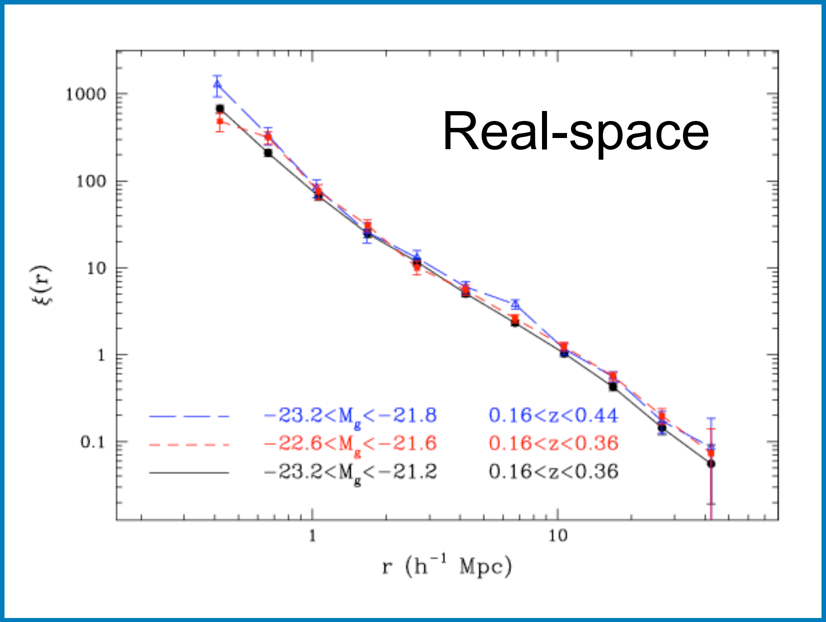


# A Volume-Limited Sample



# Intermediate-scale Correlations



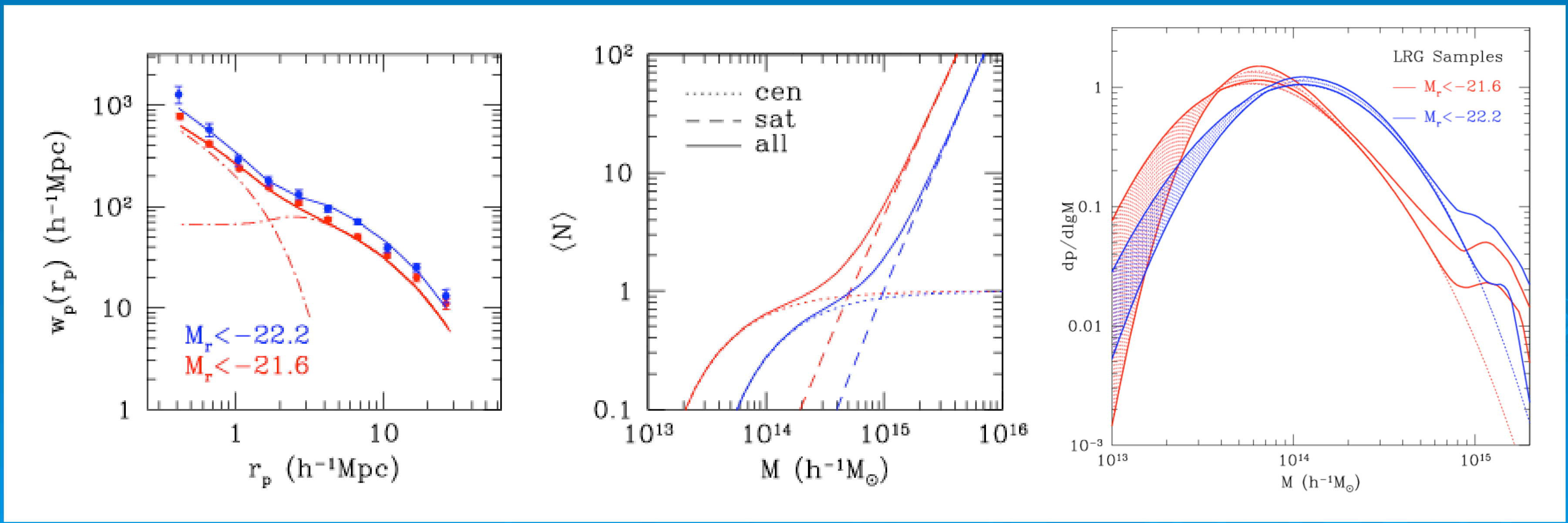




Zehavi et al. (2004)

- Subtle luminosity dependence in amplitude.
  - $\sigma_8$ = 1.80±0.03 up to 2.06±0.06 across samples
  - $r_0 = 9.8h^{-1}$ up to $11.2h^{-1}$ Mpc
- Real-space correlation function is not a power-law.

# Halo Occupation Modeling

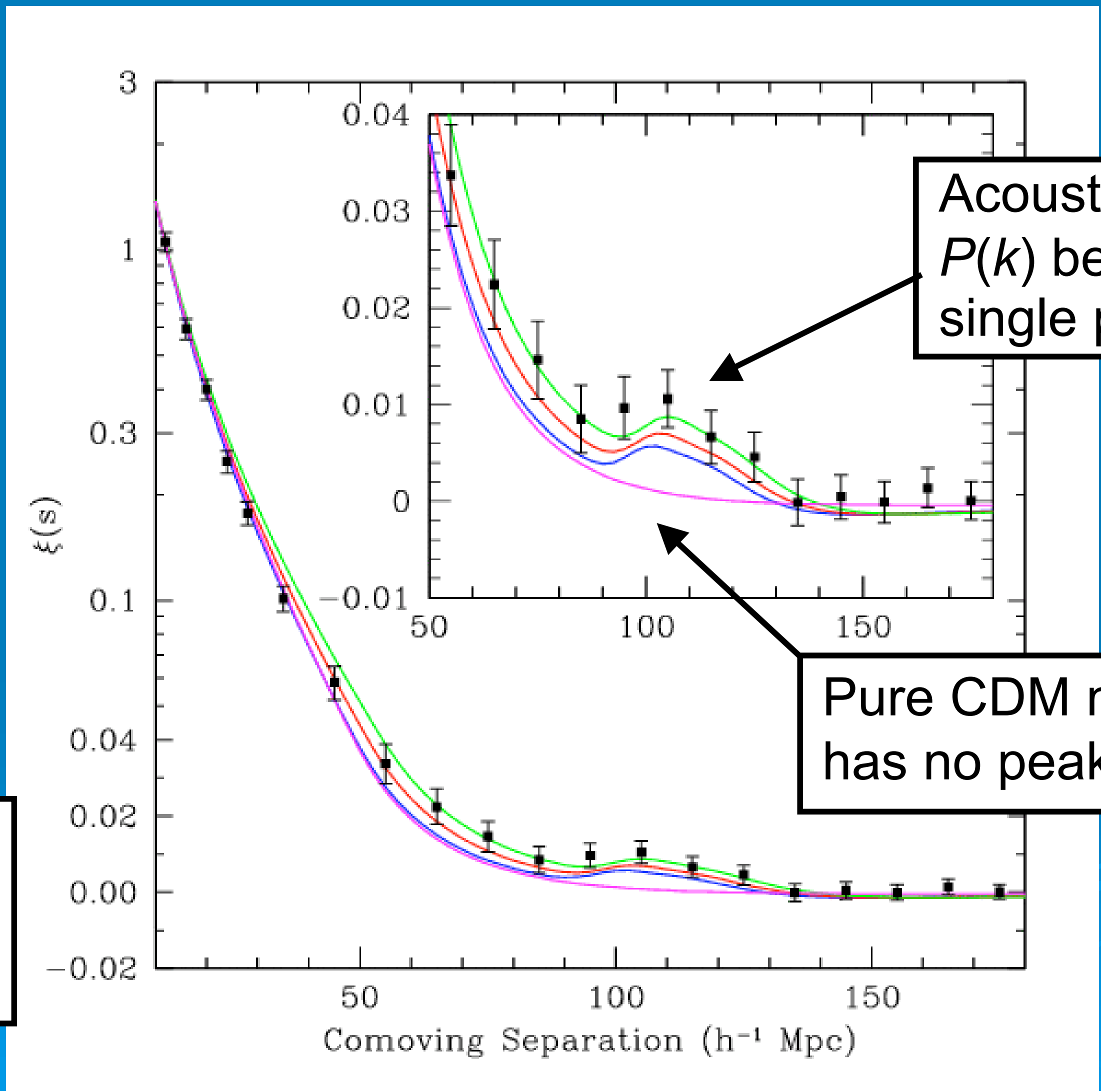
- The distribution of dark matter halo masses for the galaxies determines their clustering.
- Generically predict an inflection in $\xi(r)$.




From Zheng Zheng; similar to Zehavi et al. (2004)

# On to Larger Scales....

# Large-scale Correlations

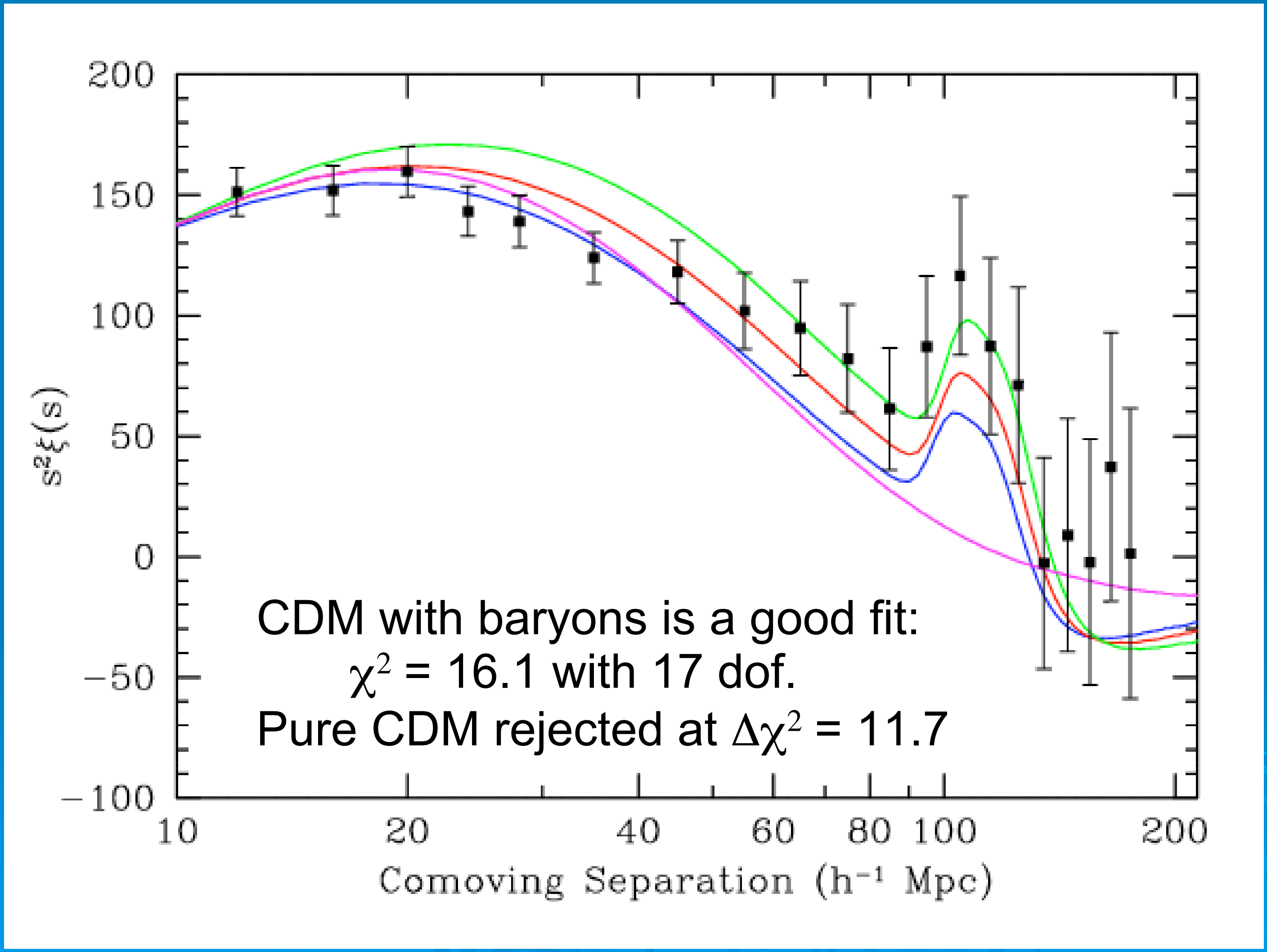



Acoustic series in *P*(*k*) becomes a single peak in *ξ*(*r*)!

Pure CDM model has no peak.

Warning: Correlated Error Bars

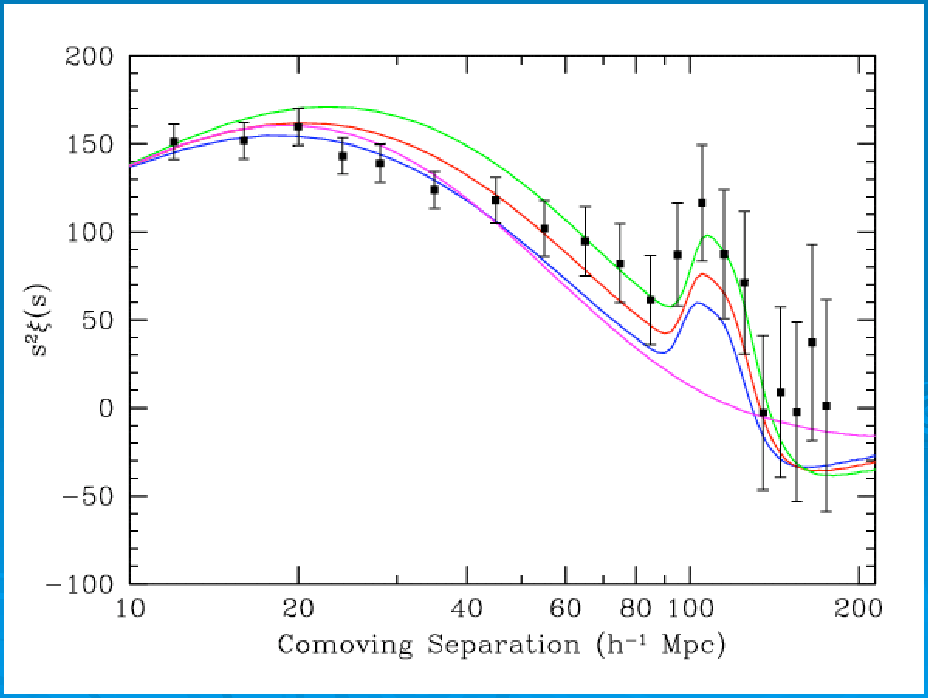
# Another View



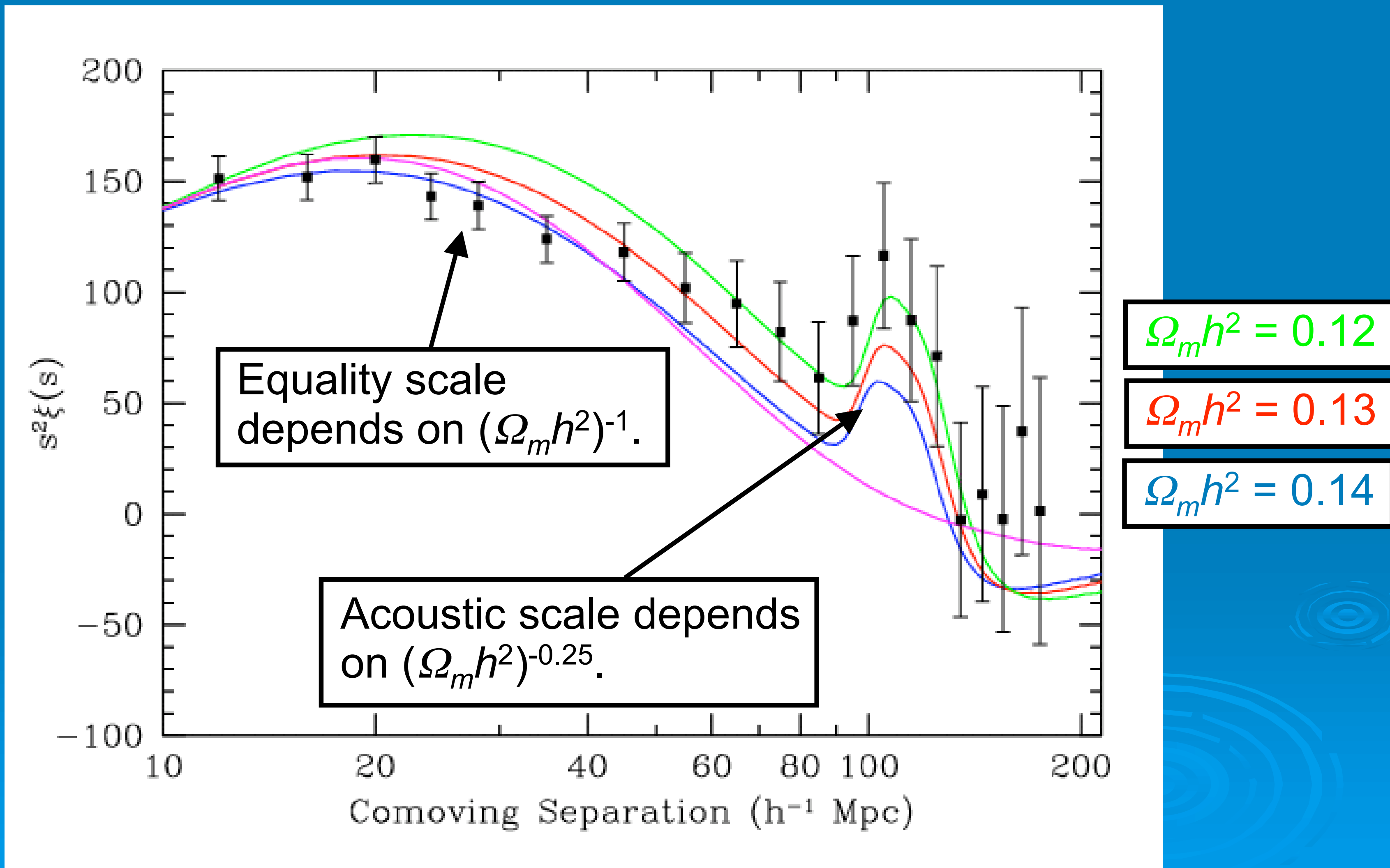
# A Prediction Confirmed!

- Standard inflationary CDM model requires acoustic peaks.
  - Important confirmation of basic prediction of the model.

- This demonstrates that structure grows from z=1000 to z=0 by linear theory.
  - Survival of narrow feature means no mode coupling.



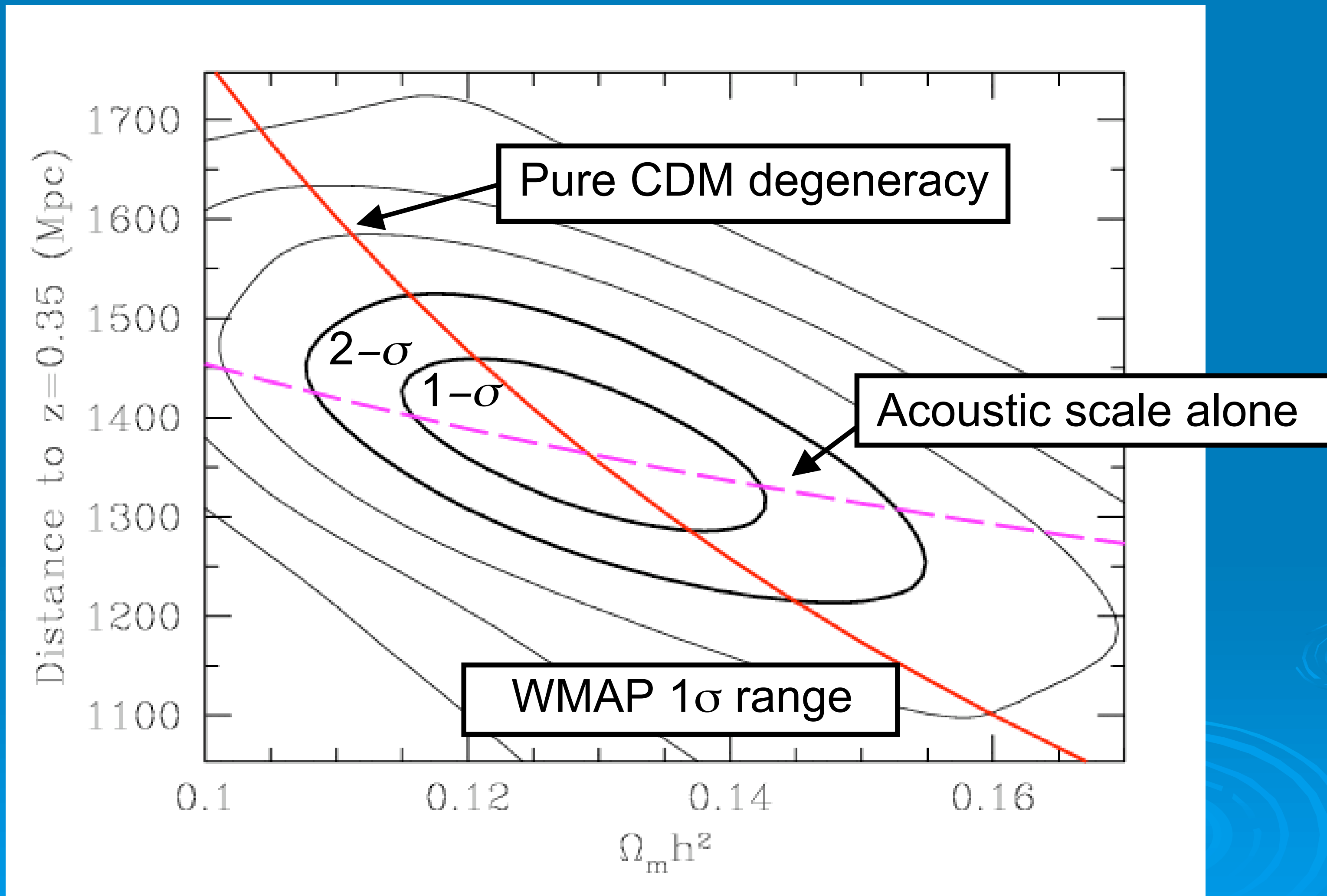
# Two Scales in Action



# Parameter Estimation

- Vary $\Omega_m h^2$ and the distance to $z = 0.35$, the mean redshift of the sample.
  - Dilate transverse and radial distances together, i.e., treat $D_A(z)$ and $H(z)$ similarly.
- Hold $\Omega_b h^2 = 0.024$, $n = 0.98$ fixed (WMAP).
  - Neglect info from CMB regarding $\Omega_m h^2$, ISW, and angular scale of CMB acoustic peaks.
- Use only $r > 10h^{-1}$ Mpc.
  - Minimize uncertainties from non-linear gravity, redshift distortions, and scale-dependent bias.
- Covariance matrix derived from 1200 PTHalos mock catalogs, validated by jack-knife testing.

# Cosmological Constraints



# Measuring a Known Scale

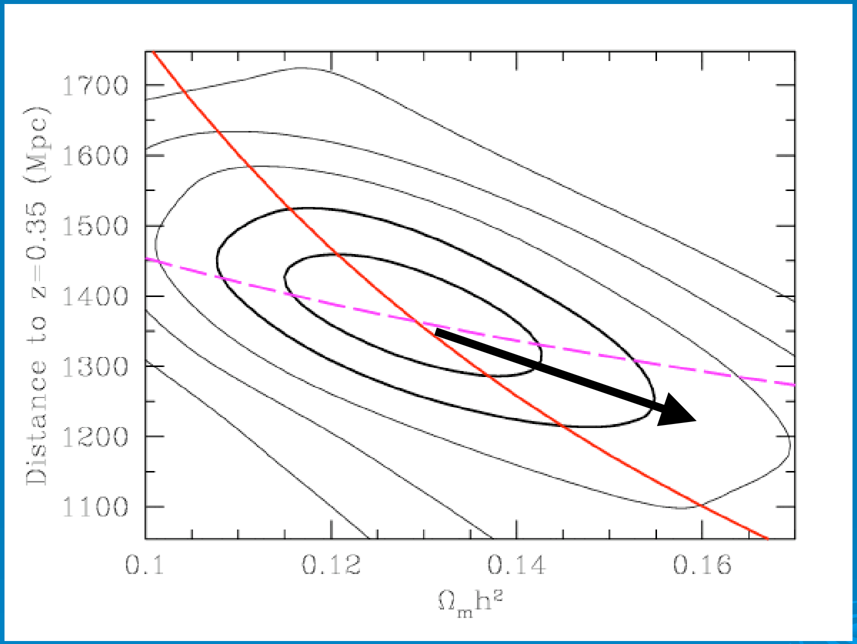
- For a given $\Omega_m h^2$, the acoustic scale is known.
- We measure it in the CMB at $z$=1000 to 1% and in SDSS at $z$=0.35 to 4%.
- This constrains $\Omega_m$, $\Omega_K$, and dark energy in two separate redshift ranges: 0<$z$<0.35 and 0.35<$z$<1000.

$$\int_0^{1000} \frac{c\,dz}{H(z)} - \int_0^{0.35} \frac{c\,dz}{H(z)} = \int_{0.35}^{1000} \frac{c\,dz}{H(z)}$$

(Flat)

# A Standard Ruler

- If the LRG sample were at $z$=0, then we would measure $H_0$ directly (and hence $\Omega_m$ from $\Omega_m h^2$).
- Instead, there are small corrections from $w$ and $\Omega_K$ to get to $z$=0.35.
- The uncertainty in $\Omega_m h^2$ makes it better to measure $(\Omega_m h^2)^{1/2} D$. This is independent of $H_0$.



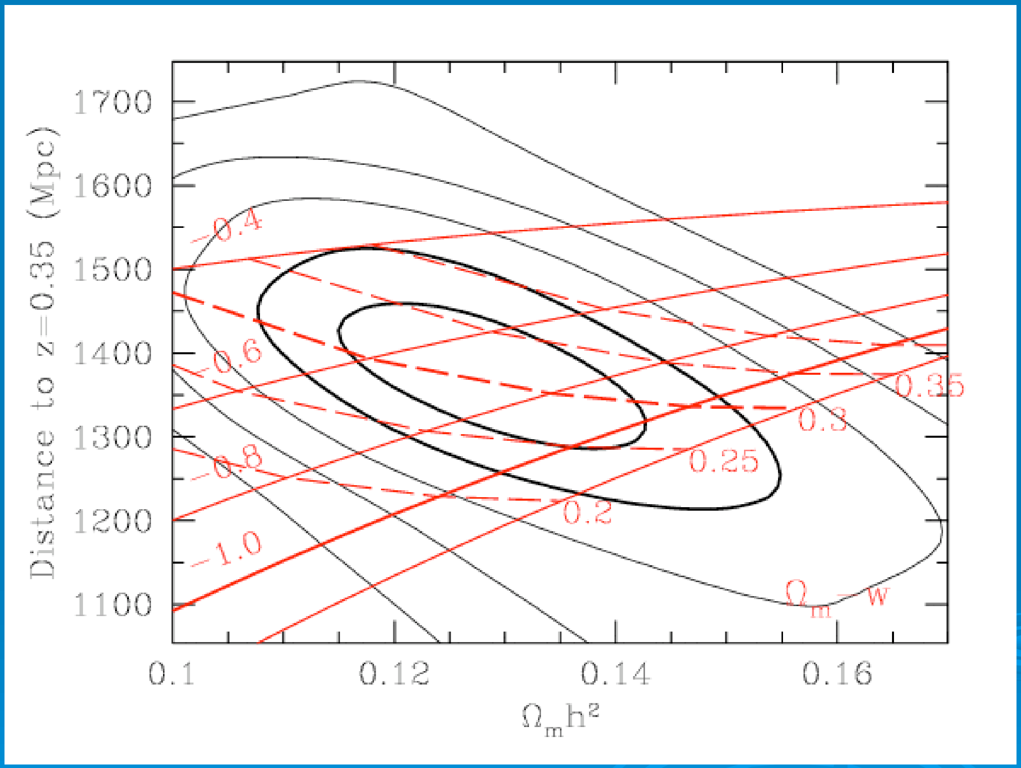

- We find $\Omega_m = 0.273 \pm 0.025 + 0.123(1+w_0) + 0.137\Omega_K$.

# Essential Conclusions

- SDSS LRG correlation function does show a plausible acoustic peak.
- Ratio of $D(z=0.35)$ to $D(z=1000)$ measured to 4%.
  - This measurement is insensitive to variations in spectral tilt and small-scale modeling. We are measuring the same physical feature at low and high redshift.
- $\Omega_m h^2$ from SDSS LRG and from CMB agree. Roughly 10% precision.
  - This will improve rapidly from better CMB data and from better modeling of LRG sample.
- $\Omega_\mathrm{m} = 0.273 \pm 0.025 + 0.123(1+w_0) + 0.137\Omega_K$.

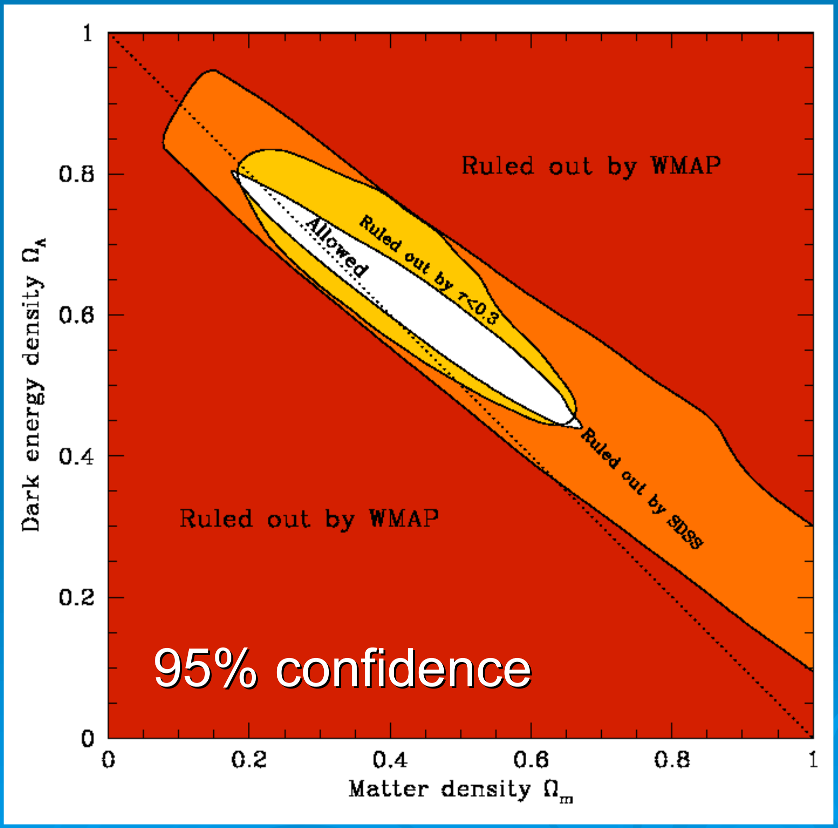
# Constant $w$ Models

- For a given $w$ and $\Omega_m h^2$, the angular location of the CMB acoustic peaks constrains $\Omega_m$ (or $H_0$), so the model predicts $D_A(z=0.35)$.
- Good constraint on $\Omega_m$, less so on $w$ (–0.8±0.2).



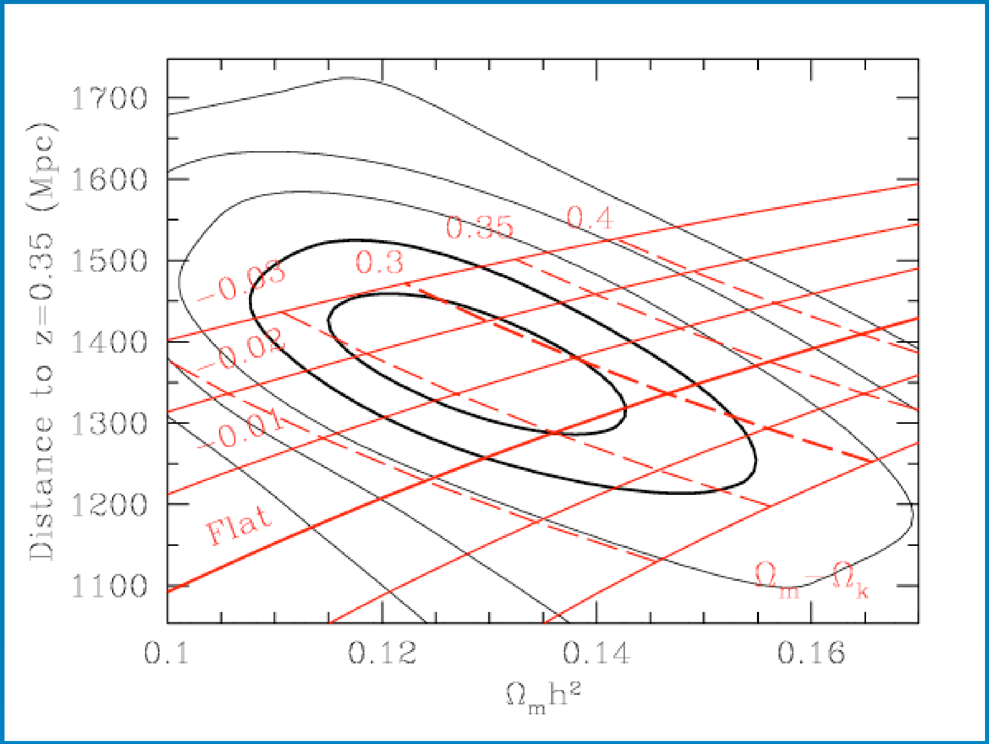
# Λ + Curvature

- Consider models with $w = -1$ (aka, Λ) but with non-zero curvature.




Tegmark et al. (2004)

# Λ + Curvature



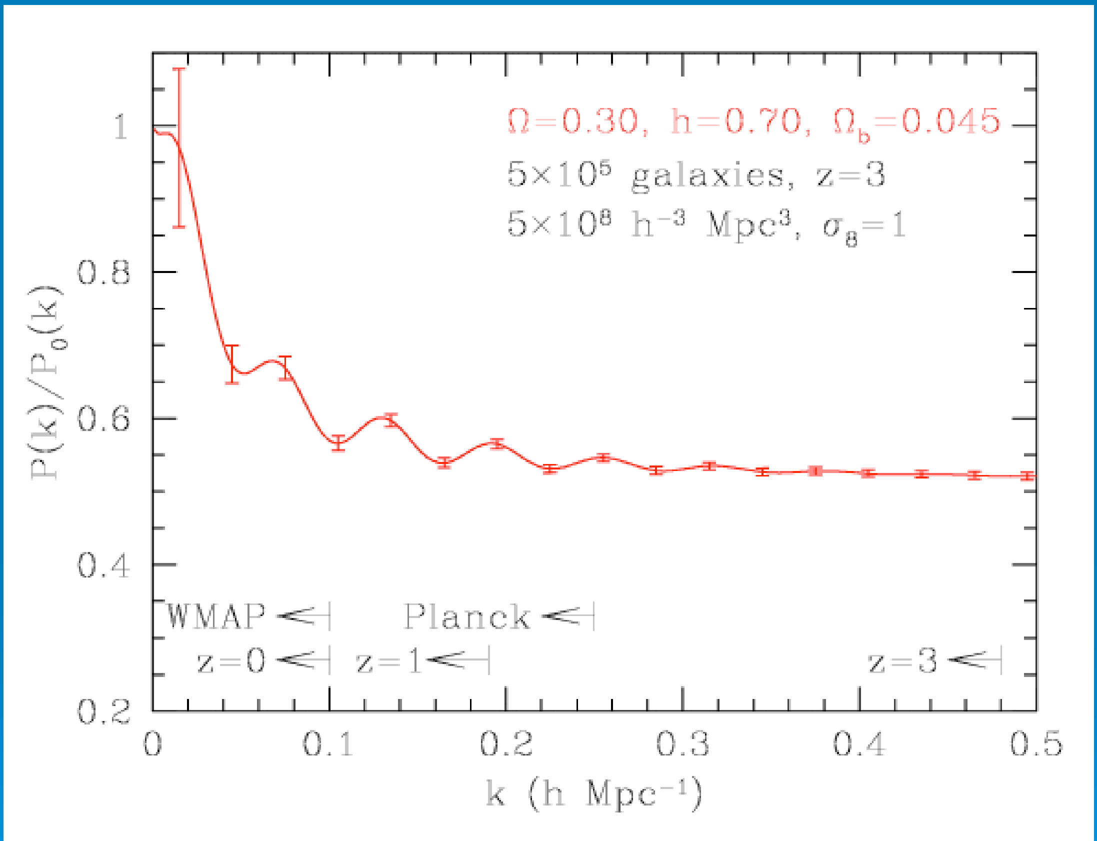

- Common distance scale to low and high redshift yields a powerful constraint on spatial curvature:

$$\Omega_K = -0.010 \pm 0.009 \quad (w = -1)$$

# Beyond SDSS

- By performing large spectroscopic surveys at higher redshifts, we can measure the acoustic oscillation standard ruler across cosmic time.
- Higher harmonics are at $k$~0.2$h$ Mpc$^{-1}$ ($\lambda$=30 Mpc)
- Measuring 1% bandpowers in the peaks and troughs requires about 1 Gpc$^3$ of survey volume with number density ~10$^{-3}$ comoving $h^3$ Mpc$^{-3}$ = ~1 million galaxies!
- We have considered surveys at $z$=1 and $z$=3.
  - Hee-Jong Seo & DJE (2003, ApJ, 598, 720)
  - Also: Blake & Glazebrook (2003), Linder (2003), Hu & Haiman (2003).

# A Baseline Survey at $z = 3$

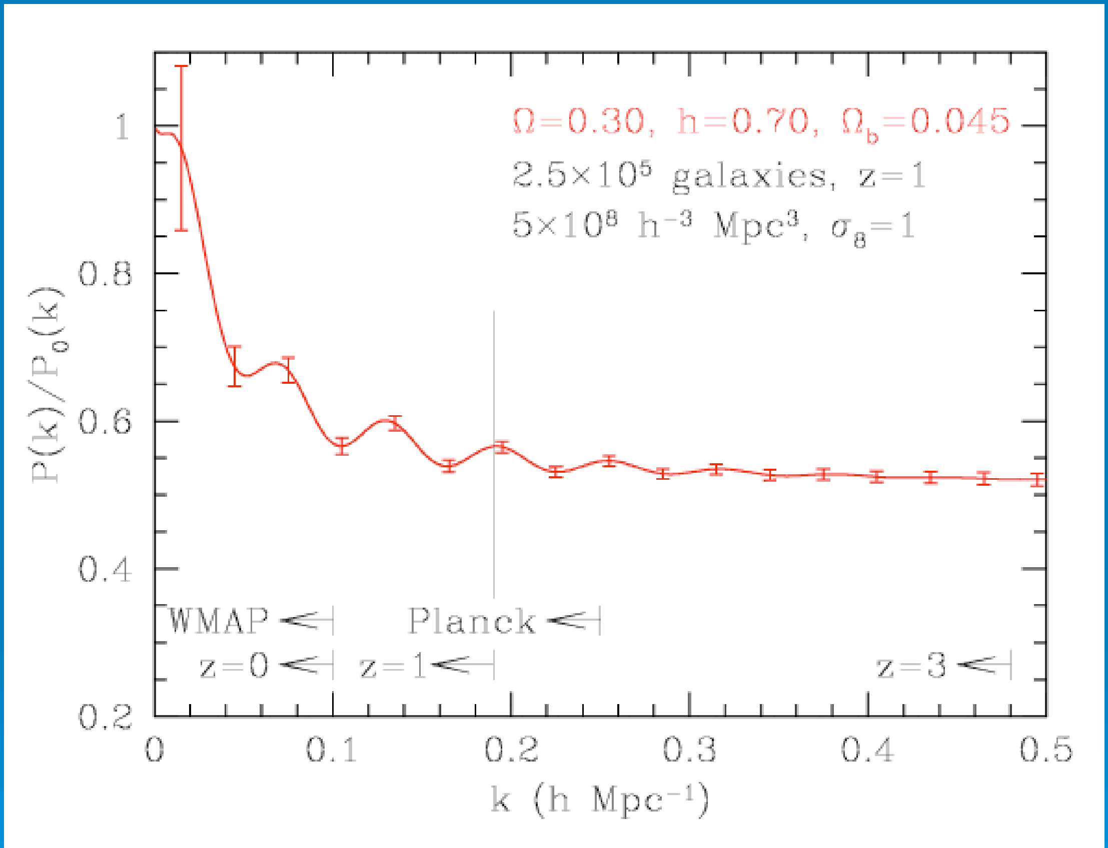



Statistical Errors from the $z$=3 Survey

- 600,000 gal.
- ~300 sq. deg.
- $10^9$ Mpc$^3$
- 0.6/sq. arcmin

- Linear regime $k$<0.3h Mpc$^{-1}$
- 4 oscillations

# A Baseline Survey at $z$ = 1




Statistical Errors from the $z$=1 Survey

- 2,000,000 gal., $z$ = 0.5 to 1.3
- 2000 sq. deg.
- $4\times10^9$ $Mpc^3$
- 0.3/sq. arcmin

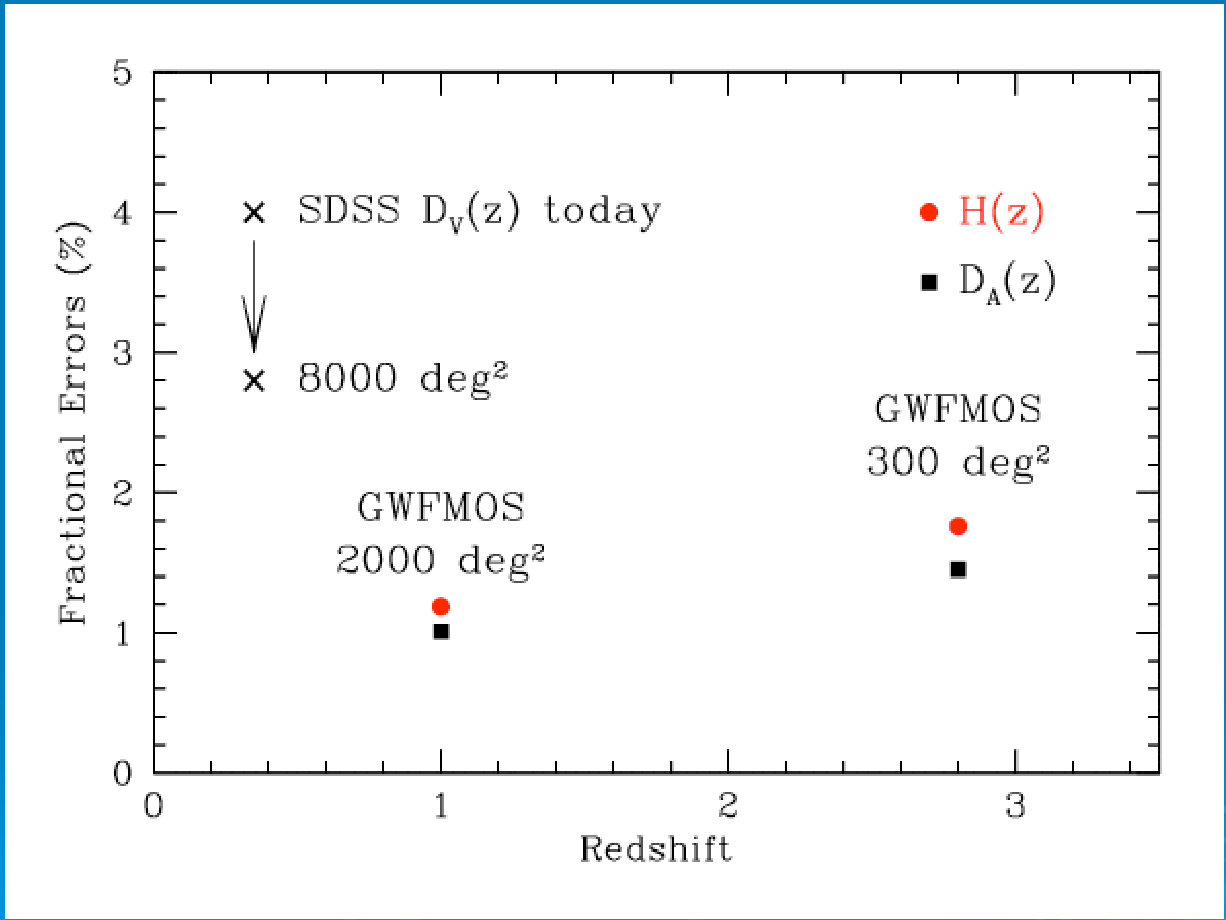
- Linear regime $k$<0.2h $Mpc^{-1}$
- 2-3 oscillations

# Methodology

**Hee-Jong Seo & DJE (2003)**

- Fisher matrix treatment of statistical errors.
  - Full three-dimensional modes including redshift and cosmological distortions.
  - Flat-sky and Tegmark (1997) approximations.
  - Large CDM parameter space: $\Omega_m h^2$, $\Omega_b h^2$, $n$, $T/S$, $\Omega_m$, plus separate distances, growth functions, $\beta$, and anomalous shot noises for all redshift slices.
- Planck-level CMB data
- Combine data to predict statistical errors on $w(z) = w_0 + w_1 z$.

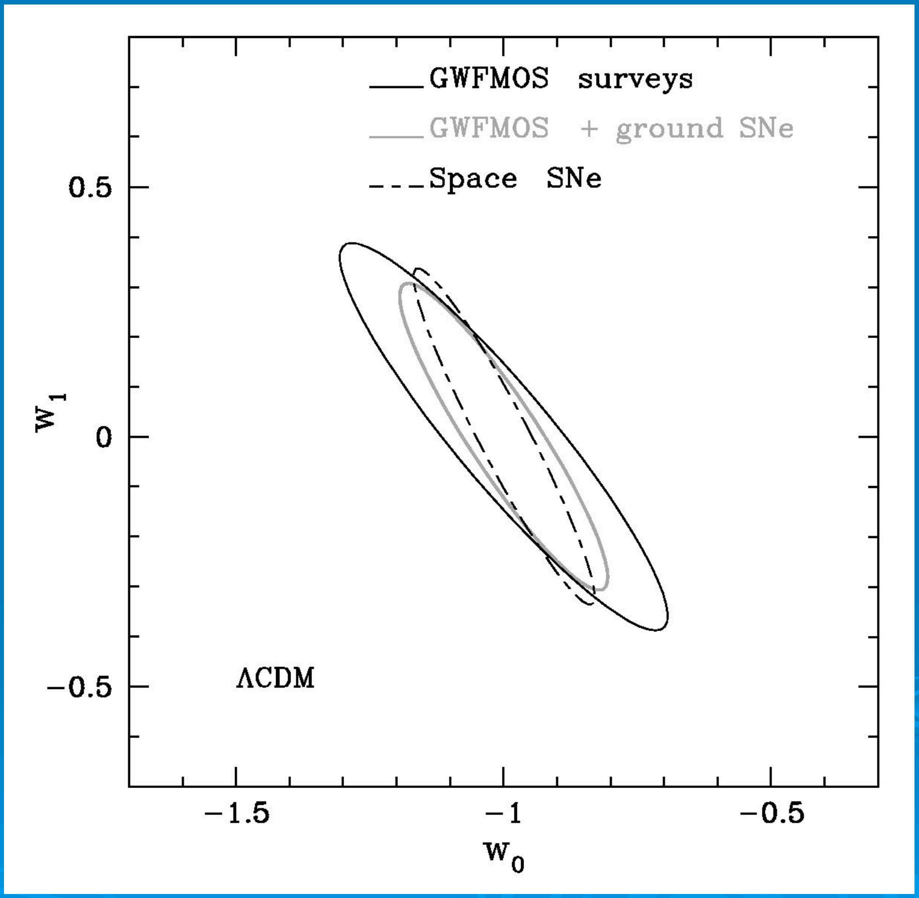
# Baseline Performance




Distance Errors versus Redshift

# Results for $\Lambda$CDM

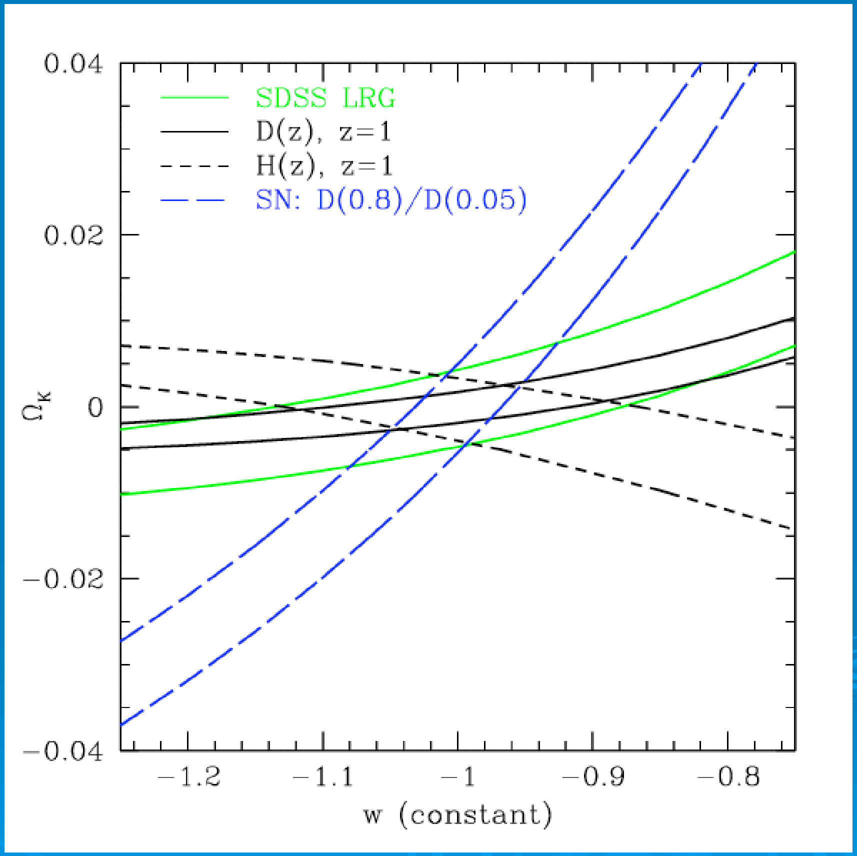
- Data sets:
  - CMB (*Planck*)
  - SDSS LRG ($z$=0.35)
  - Baseline $z$=1
  - Baseline $z$=3
  - SNe (1% in $\Delta z$=0.1 bins to $z$=1 for ground, 1.7 for space)
- $\sigma(\Omega_m)$ = 0.027
  $\sigma(w)$= 0.08 at $z$=0.7
  $\sigma(dw/dz)$ = 0.26
- $\sigma(w)$= 0.05 with ground SNe




Dark Energy Constraints in $\Lambda$CDM

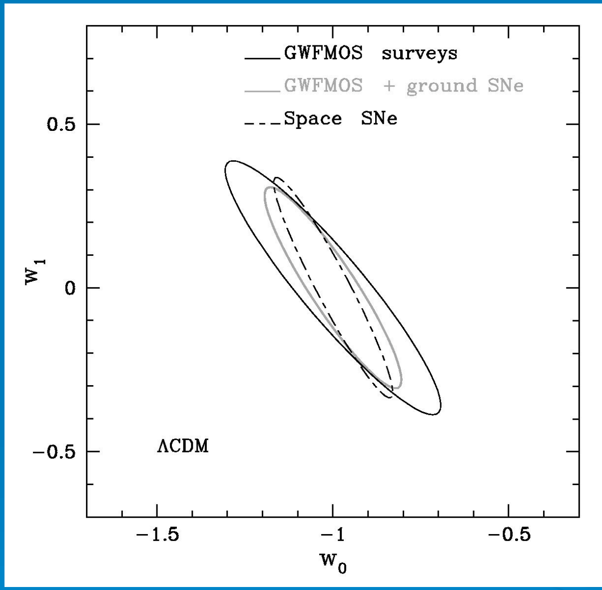
# Breaking the *w*-Curvature Degeneracy

- To prove $w \neq -1$, we should exclude the possibility of a small spatial curvature.
- SNe alone, even with space, do not do this well.
- SNe plus acoustic oscillations do very well, because the acoustic oscillations connect the distance scale to z=1000.



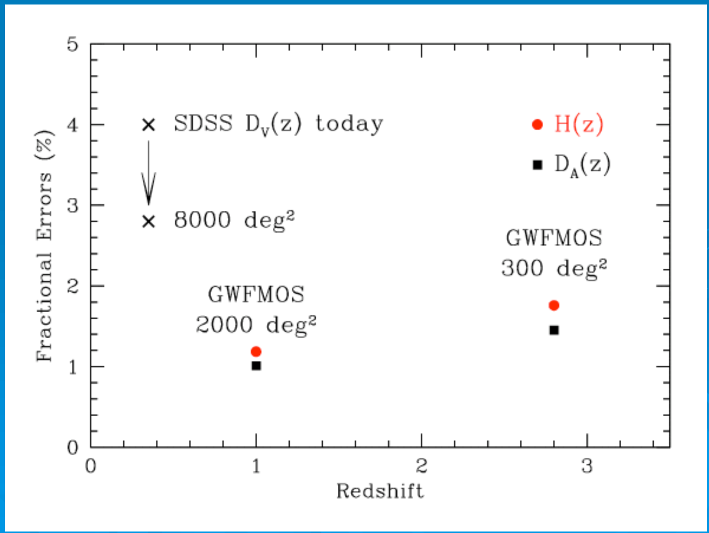
# How best to measure H(1)?

- These baseline surveys plus ground SNe measurement of D(0.8)/D(0.5) to 1% (2% in flux) predict the value of D(1.7)/D(0.8) to 0.6% (1.2% in flux) for a very general w(z)+ curvature model.
- Not surprising that D(1.7)/D(0.8) is essentially the same as H($z$=1)/$H_0$.
- Ground-based acoustic oscillations may be completely degenerate with higher redshift SNe.



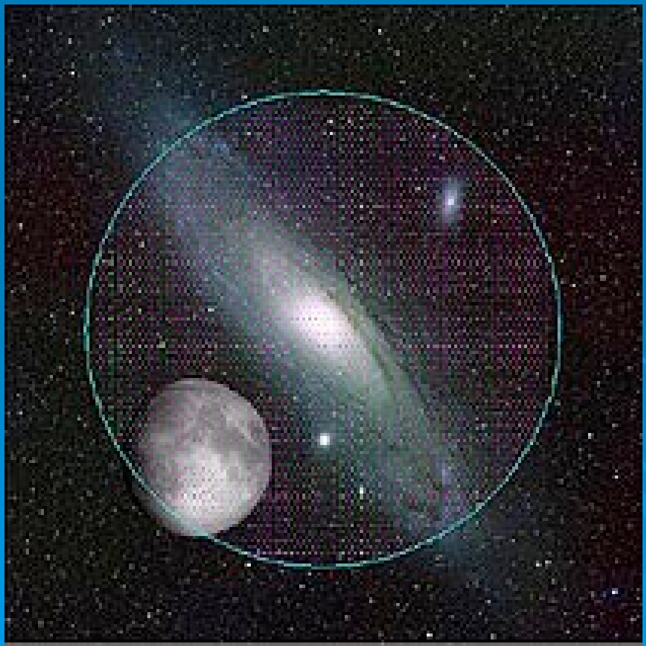
# Opening Discovery Spaces

- With 3 redshift surveys, we actually measure dark energy in 4 redshift ranges: 0<z<0.35, 0.35<z<1, 1<z<3, and 3<z<1000.
- SNe should do better at pinning down $D(z)$ at $z<1$. But acoustic method opens up high $z$ and H(z) to find the unexpected.
- Weak lensing, clusters also focus on $z<1$. These depend on growth of structure. We would like both a growth and a kinematic probe to look for changes in gravity.



# A Better Mousetrap

- How to survey a million galaxies at $z = 1$ over 1000 sq. deg? Or half a million at $z = 3$ over 300 sq. deg?
- This is a large step over on-going surveys, but it is a reasonable goal for the coming decade.
- KAOS spectrograph concept for Gemini (GWFMOS) could do these surveys in a year.
  - 4000-5000 fibers, using Echidna technology, feeding multiple bench spectrographs.
  - 1.5 degree diameter FOV
  - http://www.noao.edu/kaos
  - Well ranked in Aspen process.
  - Also high-res for Galactic studies.
  - Currently finishing feasibility study.



# Other Spectroscopic Options

- Near-term
  - Second half of SDSS
  - AAOmega: LRGs at $z$=0.6
  - FMOS: H$\alpha$ at z=1.5
- Next Generation
  - WFMOS: z=1 & z=3
  - HETDEX: Ly$\alpha$ at $z$=2–3
- Lyman $\alpha$ forest?
- Towards full sky
  - BOP: H$\alpha$ in space, $10^4$ deg$^2$ out to $z$=2.
  - JEDI: H$\alpha$ in space up to $10^4$ deg$^2$.
  - SKA: 21 cm to $z$=1.5, full visible sky.

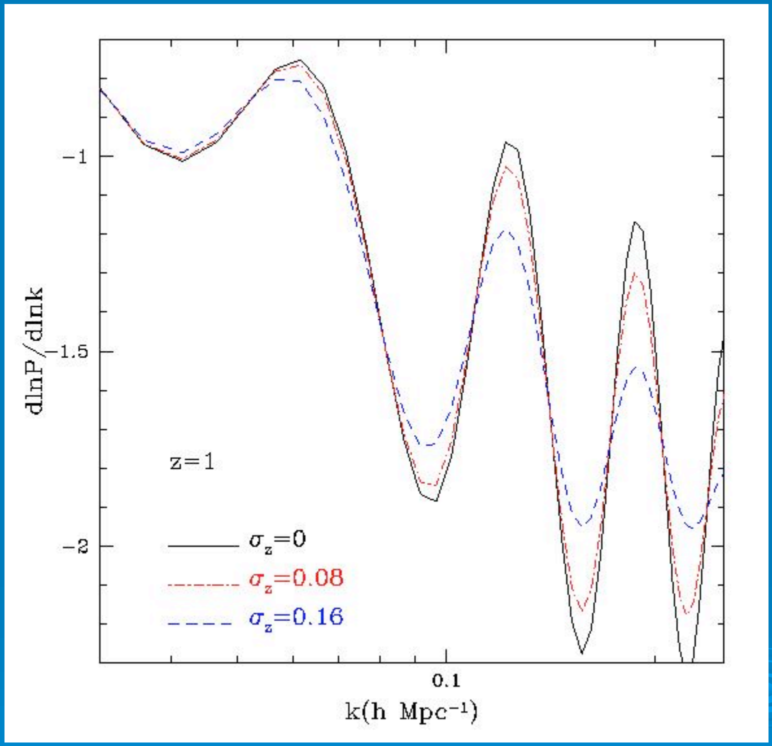
# Performance from $10^4$ deg$^2$

| | Spectro $D_A(z)$ | Spectro $H(z)$ |
|---|---|---|
| $0.5<z<0.8$ | 0.94% | 1.2% |
| $0.8<z<1.2$ | 0.46% | 0.57% |
| $1.2<z<1.8$ | 0.34% | 0.42% |
| $1.8<z<2.4$ | 0.28% | 0.35% |
| $3.0<z<4.0$ | 0.23% | 0.28% |

- Adopting $n = 0.001h^3$ Mpc$^{-3}$.
- With 1% D(0.8)/D(0.05) and z<2.4, $w_p = 0.025$, $w_a = 0.20$. Predicts D(1.7)/D(0.8) to 0.004 mag.

# Photometric Redshifts?

- Can we do this without spectroscopy?
- Measuring H(z) requires detection of acoustic oscillation scale along the line of sight.
  - Need ~10 Mpc accuracy. $\sigma_z$~0.003(1+z).
- But measuring $D_A(z)$ from transverse clustering requires only 4% in 1+*z*.
- Need ~half-sky survey to match 1000 sq. deg. of spectra.
- Less robust, but likely feasible.




4% photo-z's don't smear the acoustic oscillations.

# Cross-Correlation Cosmography

- Weak lensing cross-correlation cosmography could in principle measure $D(z)$ to superb precision (0.02% for full sky in space), save for a degeneracy of the form $\alpha_0(D + \alpha_1 D^2 + \alpha_2 D^3)$, where $\alpha_2$ depends only on $\Omega_K$. (Bernstein 2005)
  - Bad news: this is very degenerate with simple $w(z)$.
  - Good news: if one can measure $\alpha_1$ and $\alpha_2$ well by other means, then one can constrain more complicated $D(z)$ modes far better. Measuring these well may slant the optimization of surveys.
  - "Spaceship One" version: Could measure curvature independently of CMB and then use CMB acoustic scale to measure $w$ at $z$>4.

# What about $H_0$?

- Does the CMB+LSS+SNe really measure the Hubble constant? What sets the scale in the model?
  - The energy density of the CMB photons plus the assumed a neutrino background gives the radiation density.
  - The redshift of matter-radiation equality then sets the matter density ($\Omega_m h^2$).
  - Measurements of $\Omega_m$ (e.g., from distance ratios) then imply $H_0$.
- Is this good enough?

# What about $H_0$?

- What if the radiation density were different, (more/fewer neutrinos or something new)?
  - Sound horizon would be shifted in scale. LSS inferences of $\Omega_m$, $\Omega_k$, $w(z)$, etc, would be correct, but $\Omega_m h^2$ and $H_0$ would be shifted.
  - Baryon fraction would be changed ($\Omega_b h^2$ is fixed).
  - Anisotropic stress effects in the CMB would be different. This is detectable with Planck.
- So $H_0$ is either a probe of "dark radiation" or dark energy (assuming radiation sector is simple).
  - 1 neutrino species is roughly 5% in $H_0$.
  - We could get to ~1%.

DJE & White (2004)

# Pros and Cons of the Acoustic Peak Method

Advantages:

- Geometric/trigonometric measure of distance.
- Robust to systematics.
- Individual measurements are not hard (but you need a lot of them!).
- Can probe $z>2$.
- Can measure $H(z)$ directly (with spectra).

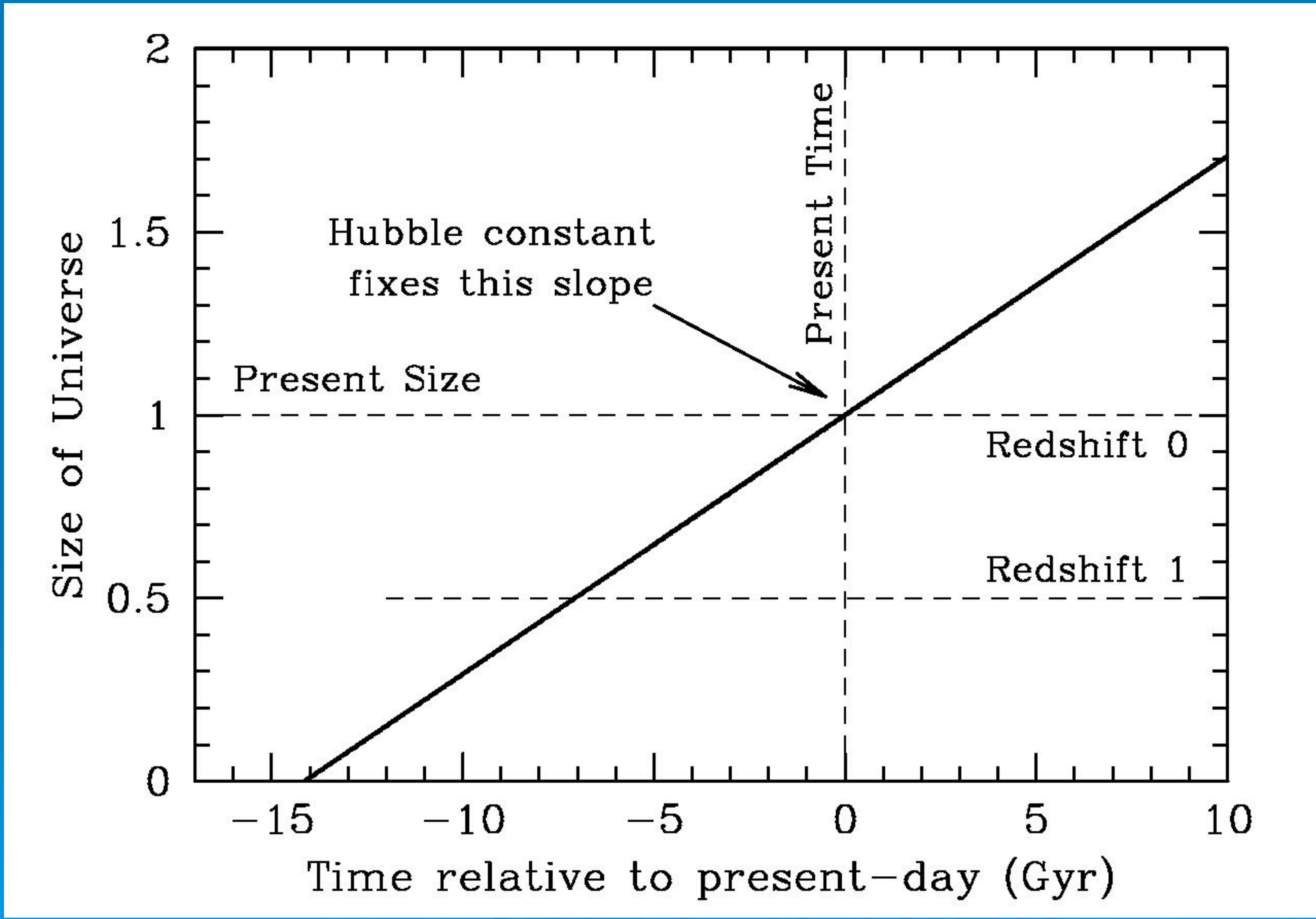
Disadvantages:

- Raw statistical precision at $z<1$ lags SNe and lensing/clusters.
  - Full sky would help.
- If dark energy is close to $\Lambda$, then $z<1$ is more interesting.
- Calibration of standard ruler requires inferences from CMB.
  - But this doesn't matter for relative distances.

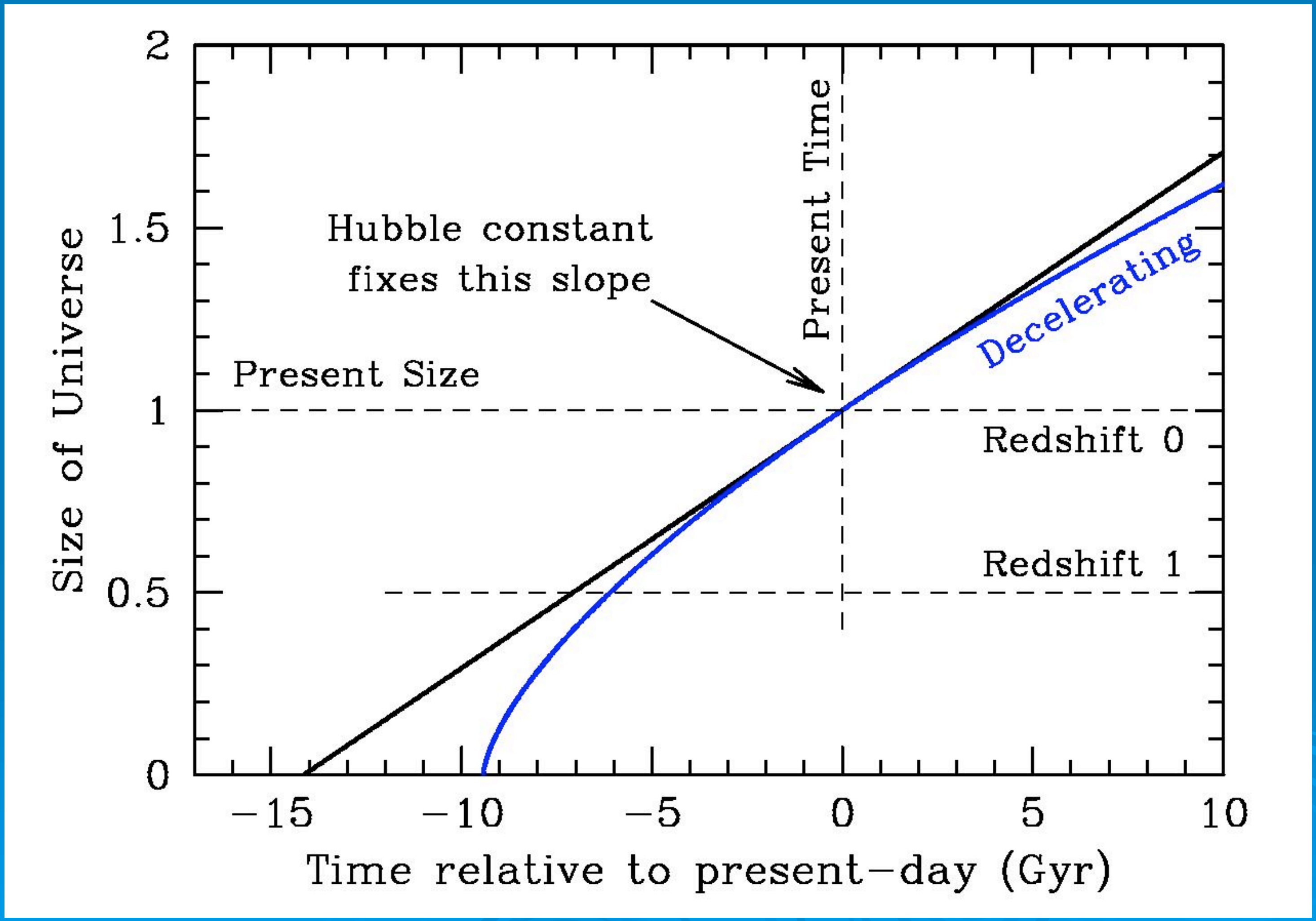
# Conclusions

- Acoustic oscillations provide a robust way to measure H(z) and $D_A(z)$.
  - Clean signature in the galaxy power spectrum.
  - Can probe high redshift.
  - Can probe H(z) directly.
  - Independent method with similar precision to SNe.
- SDSS LRG sample uses the acoustic signature to measure $D_A(z=0.35)/D_A(z=1000)$ to 4%.
- Large high-z galaxy surveys are feasible in the coming decade.
- Order from KAOS!  http://www.noao.edu/kaos

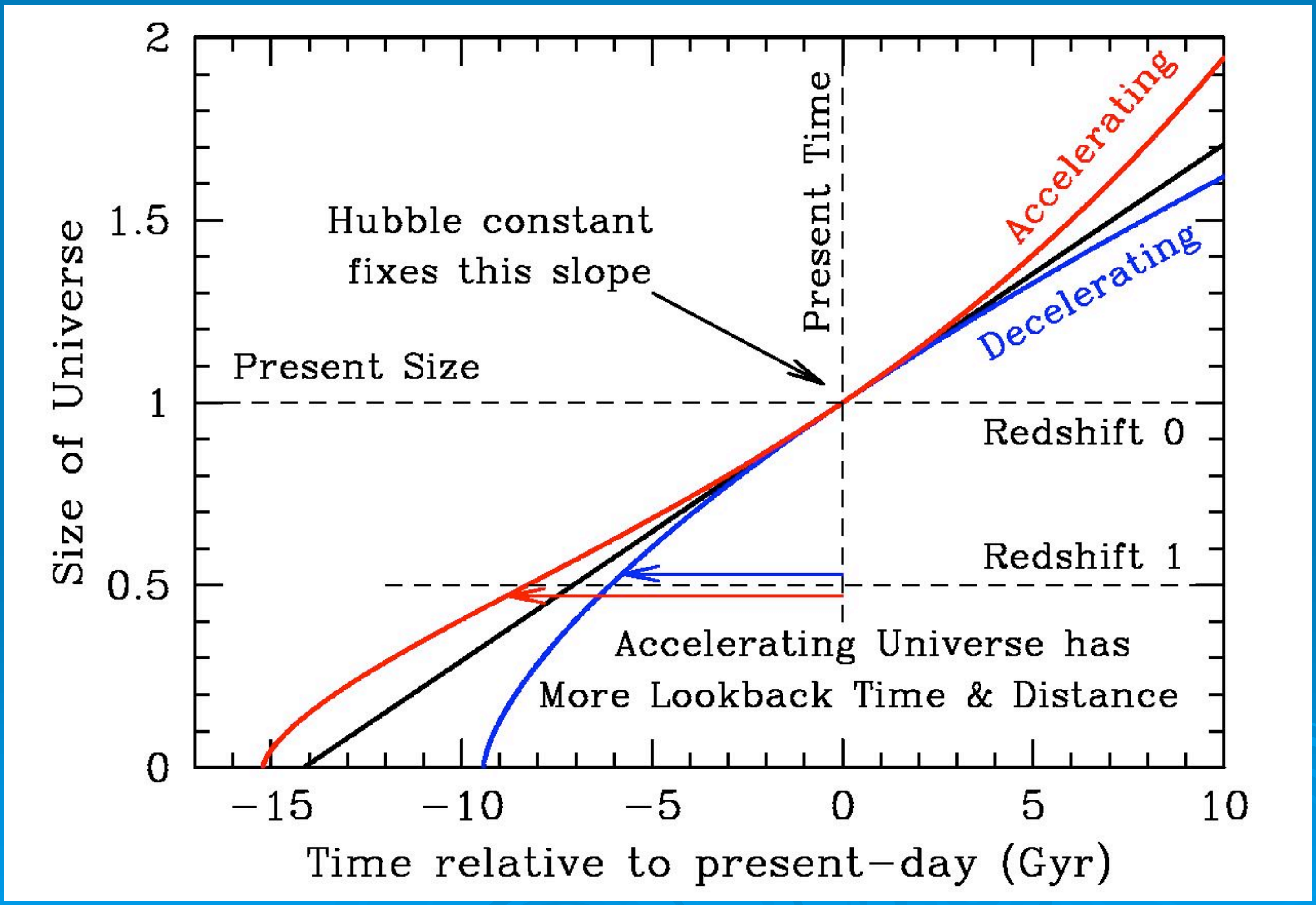
# Distances to Acceleration



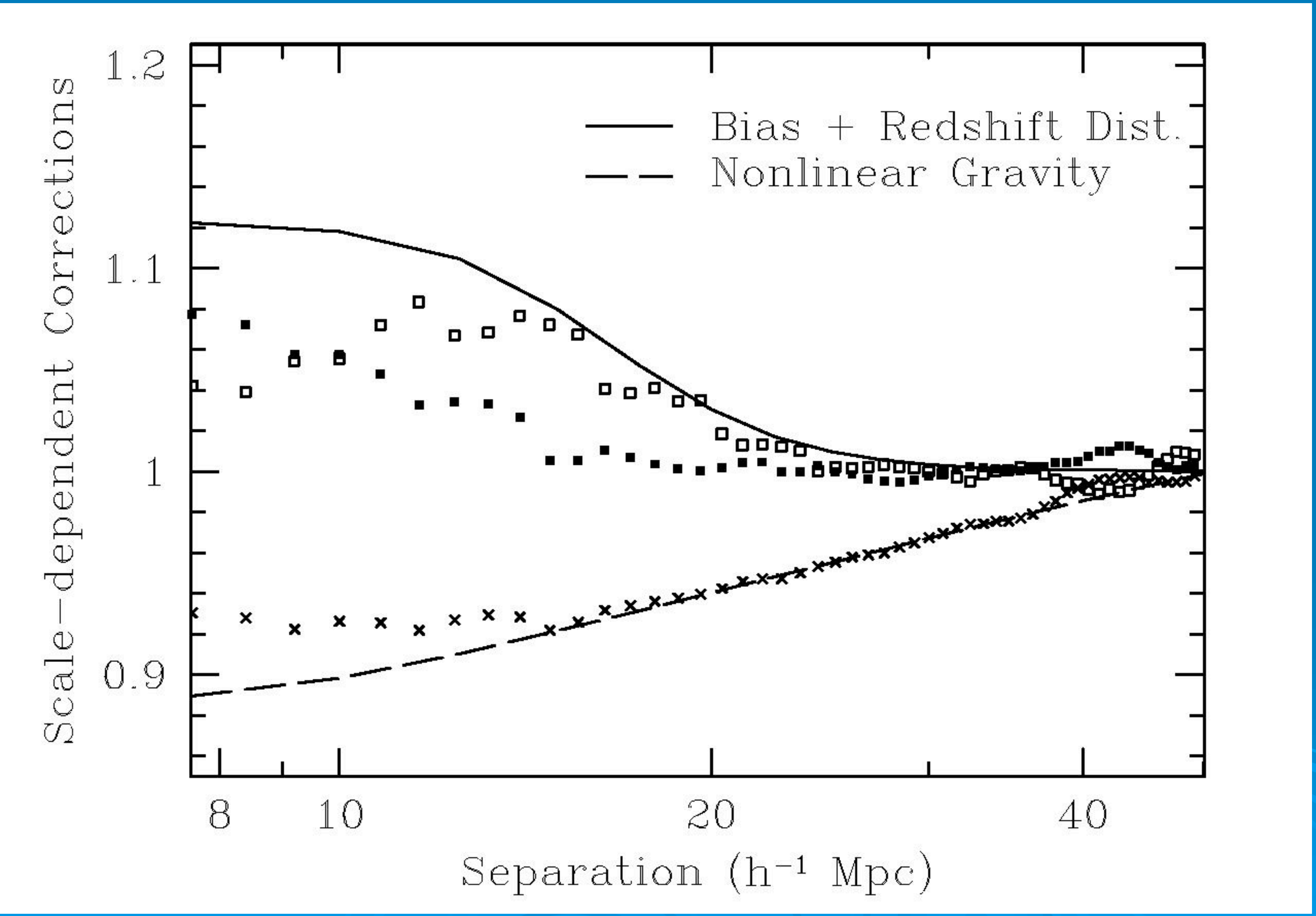
# Distances to Acceleration



# Distances to Acceleration



# Nonlinear Corrections

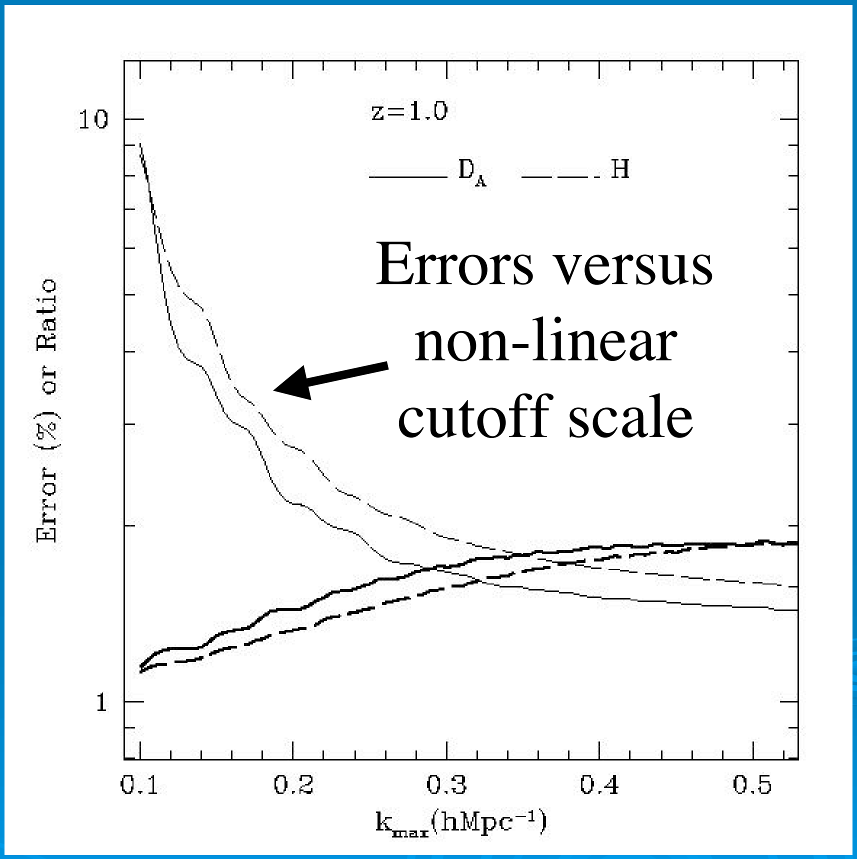


# An Optimal Number Density

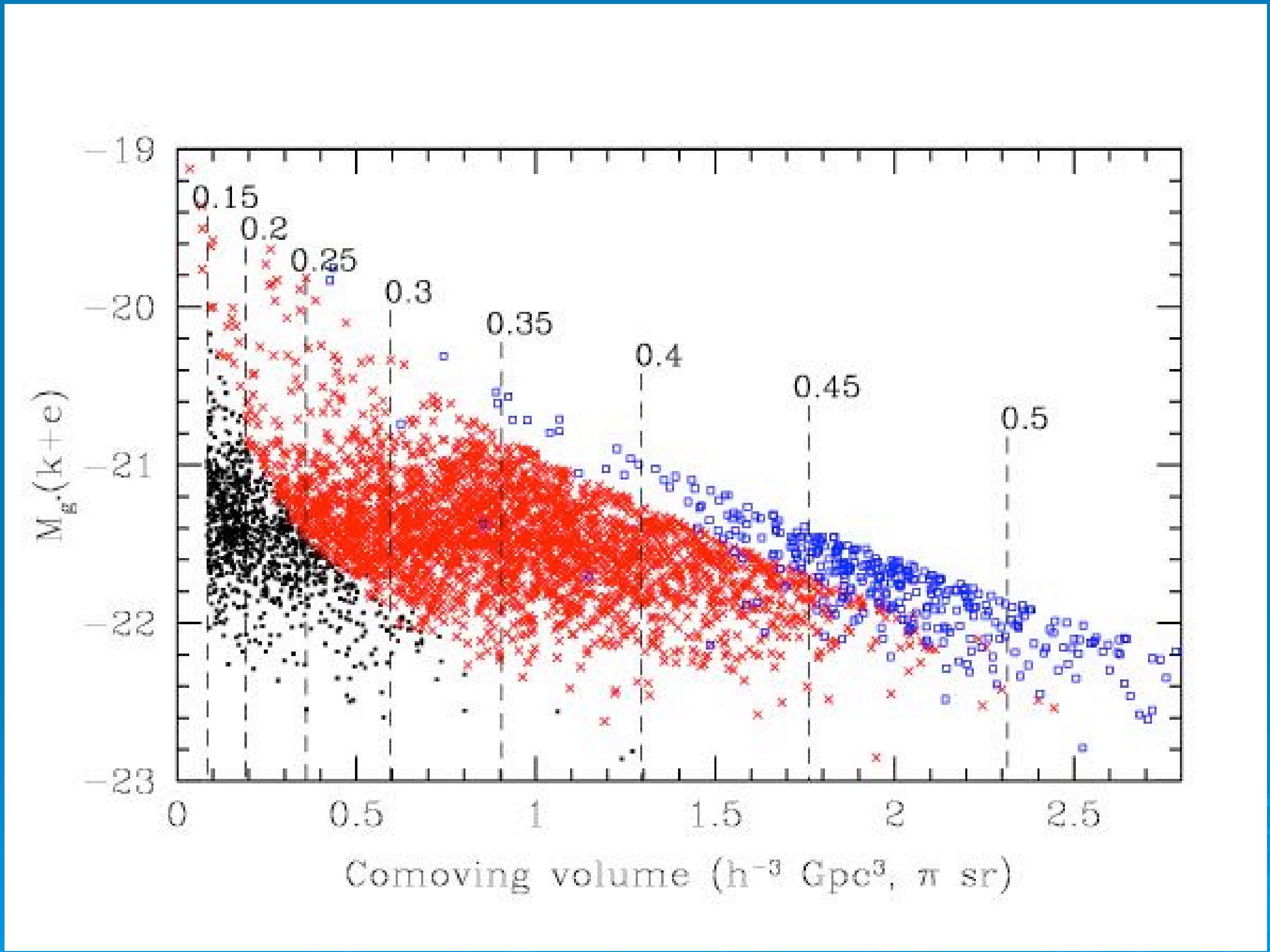
- Since survey size is at a premium, one wants to design for maximum performance.
- Statistical errors on large-scale correlations are a competition between sample variance and Poisson noise.
  - Sample variance: How many independent samples of a given scale one has.
  - Poisson noise: How many objects per sample one has.
- Given a fixed number of objects, the optimal choice for measuring the power spectrum is an intermediate density.
  - Number density roughly the inverse of the power spectrum.
    - $10^{-4}$ $h^3$ $\mathrm{Mpc}^{-3}$ at low redshift; a little higher at high redshift.
  - Most flux-limited surveys do not and are therefore inefficient for this task.

# Higher Redshifts Perform Better

- Nonlinear gravitational clustering erases the acoustic oscillations.
- This is less advanced at higher redshifts.
- Recovering higher harmonics improves the precision on distances.
- Leverage improves from $z$=0 to $z$=1.5, then saturates.

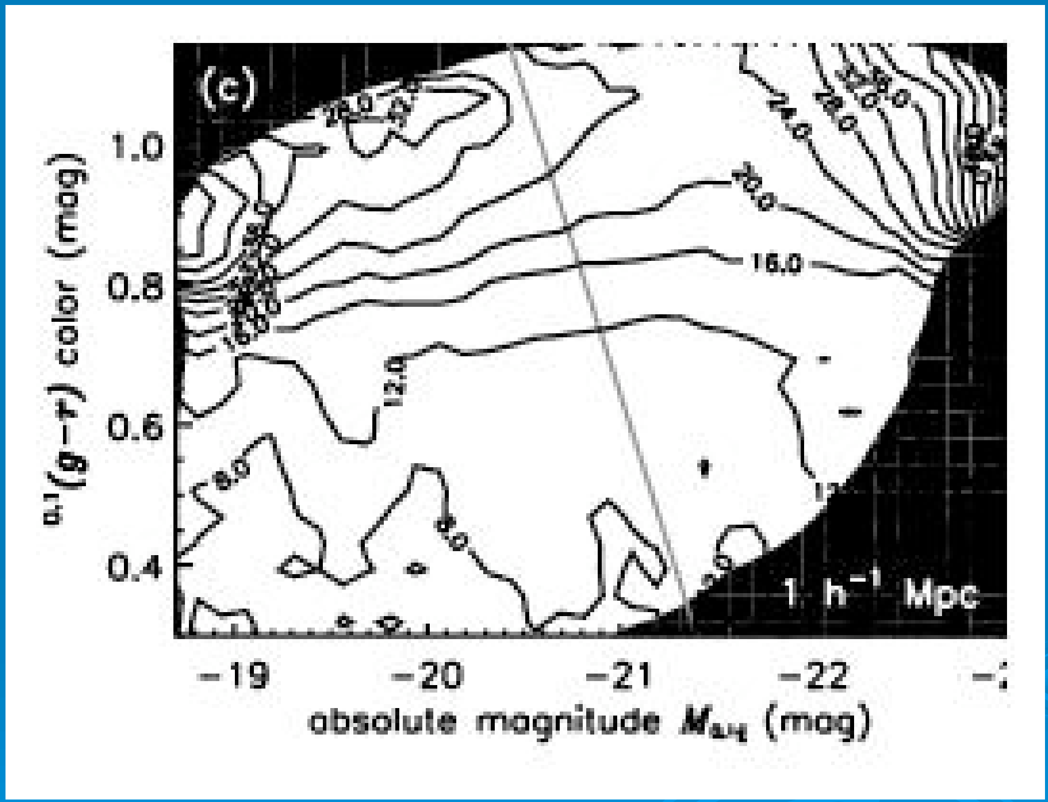


# A Volume-Limited Sample



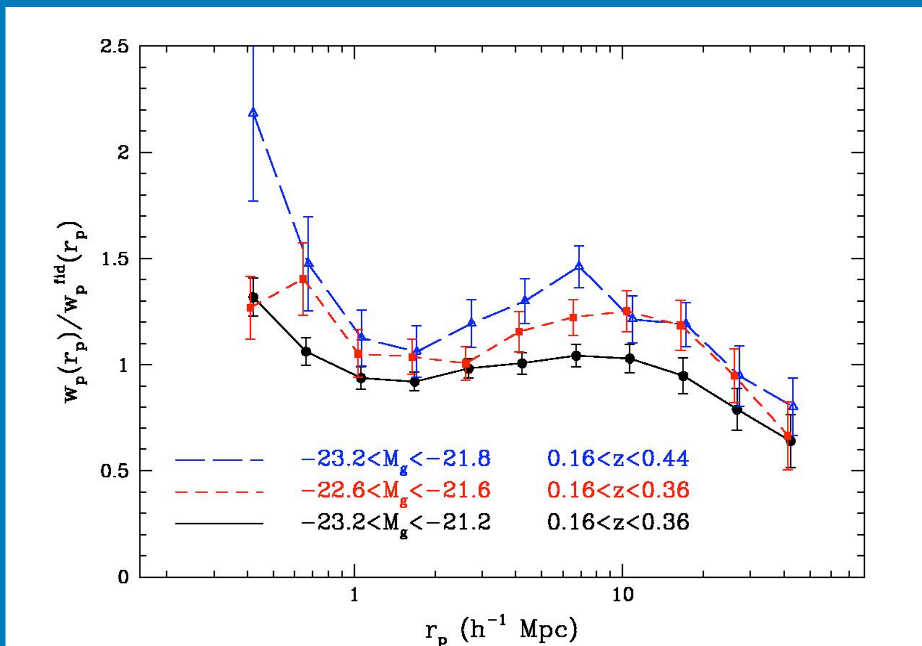
# Luminosity-dependent Bias

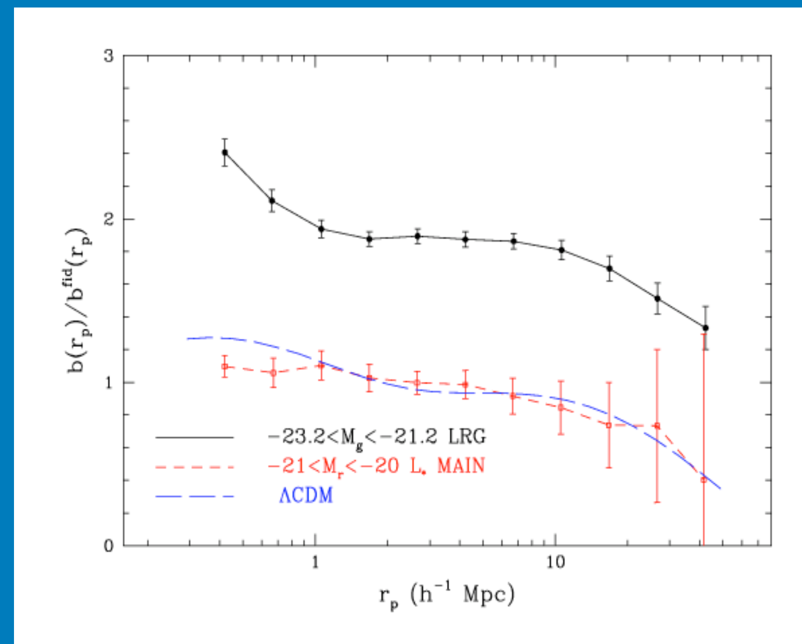
- Bias appears to change noticeably (40%?) at the luminous end, even within the narrow LRG range.
- We will need to be careful when combining $z$>0.4 and $z$<0.4.




Hogg et al. (2002)

# Real-space Correlations



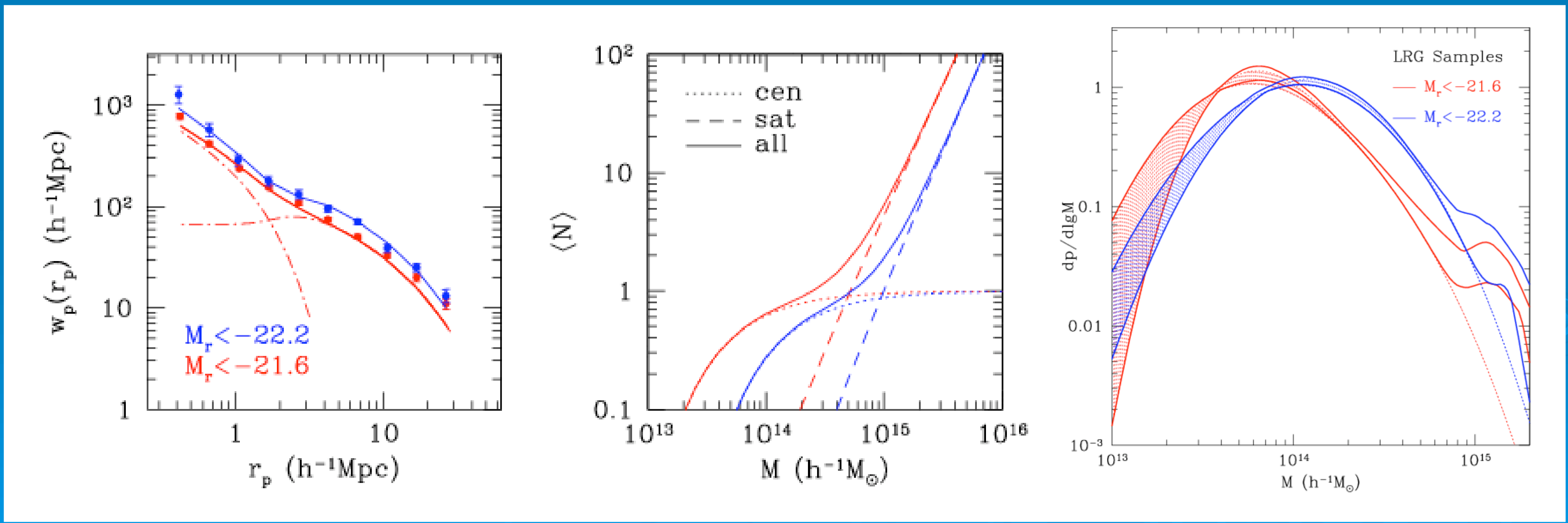




Zehavi et al. (2004)

- Obvious deviations from power laws!
- $\sigma_8$ = 1.80±0.03 up to 2.06±0.06 across samples
- $r_0$ = 9.8$h^{-1}$ up to 11.2$h^{-1}$ Mpc

# Halo Occupation Modeling

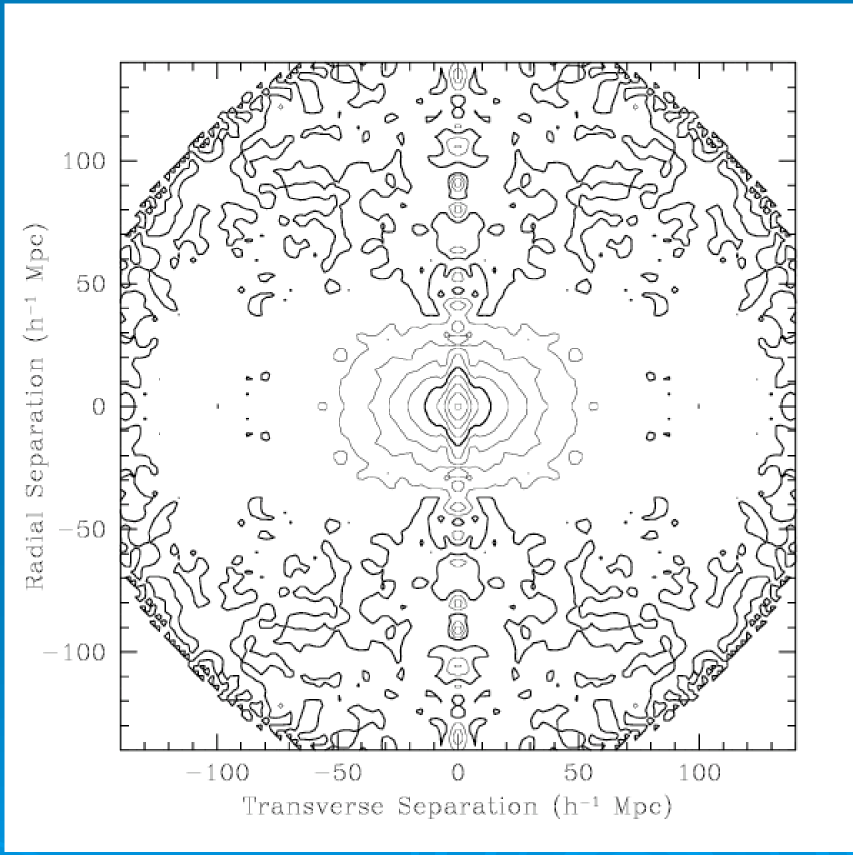
- The distribution of dark matter halo masses for the galaxies determines their clustering.
- Generically predict an inflection in $\xi(r)$.




From Zheng Zheng; similar to Zehavi et al. (2004)

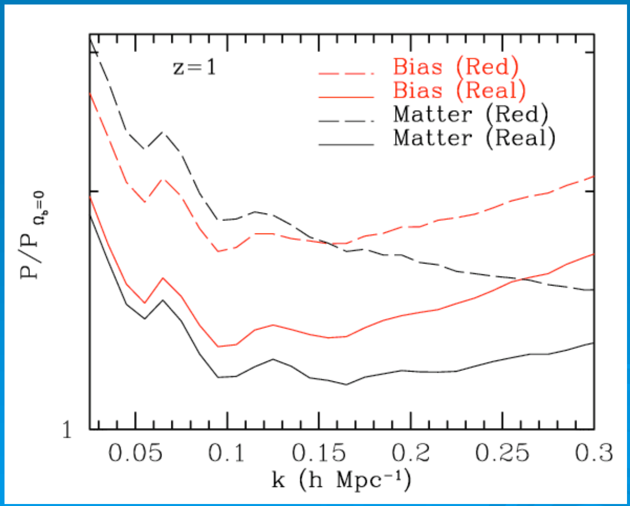
# Redshift Distortions

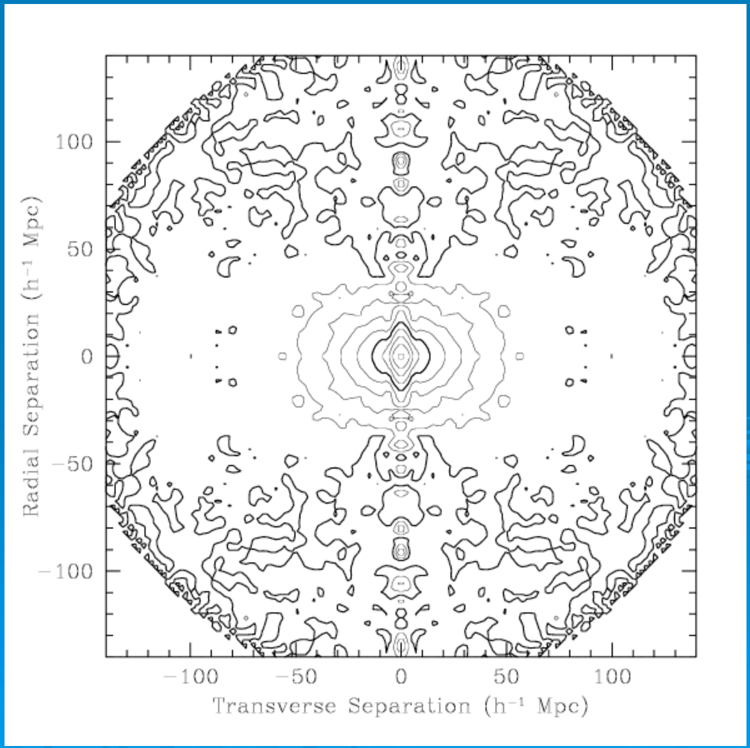
- Redshift distortions will be interesting for the study of the host halos of LRGs, but are a nuisance for the extraction of Alcock-Paczynski distortions of the isotropic power.



# Redshift Distortions

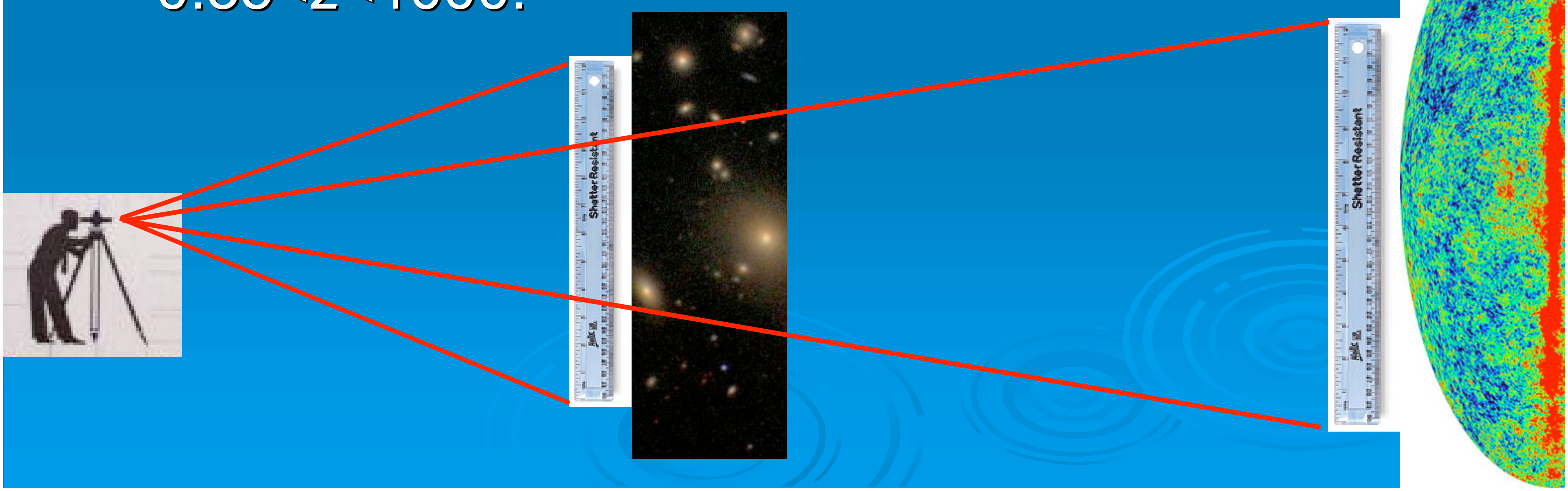
- Redshift surveys are sensitive to peculiar velocities.
- Since velocity and density are correlated, there is a distortion even on large scales.
- Correlations are squashed along the line of sight (opposite of finger of god effect).



# Measuring a Known Scale

- For a given $\Omega_m h^2$, the acoustic scale is known.
- We measure it in the CMB at $z$=1000 to 1% and in SDSS at $z$=0.35 to 4%.
- This constrains $\Omega_m$, $\Omega_K$, and dark energy in two separate redshift ranges: $0<z<0.35$ and $0.35<z<1000$.



# Constant *w* Models

- As before, but now overlaid with grid of $H_0$ and $w$.